# Power System Protection Lecture Notes

**Mohammed T. Lazim Alzuhairi**

**Professor of Electrical and Electronics Engineering**
**Electrical Engineering Department**
**Philadelphia University, Jordan**

| **Power System protection** | **Dr. Mohamad Tawfeeq** |
|---|---|
| **Introduction** | |

- Protection is the art or science of continuously monitoring the power system, detecting the presence of a fault and initiating the correct tripping of the circuit breaker.

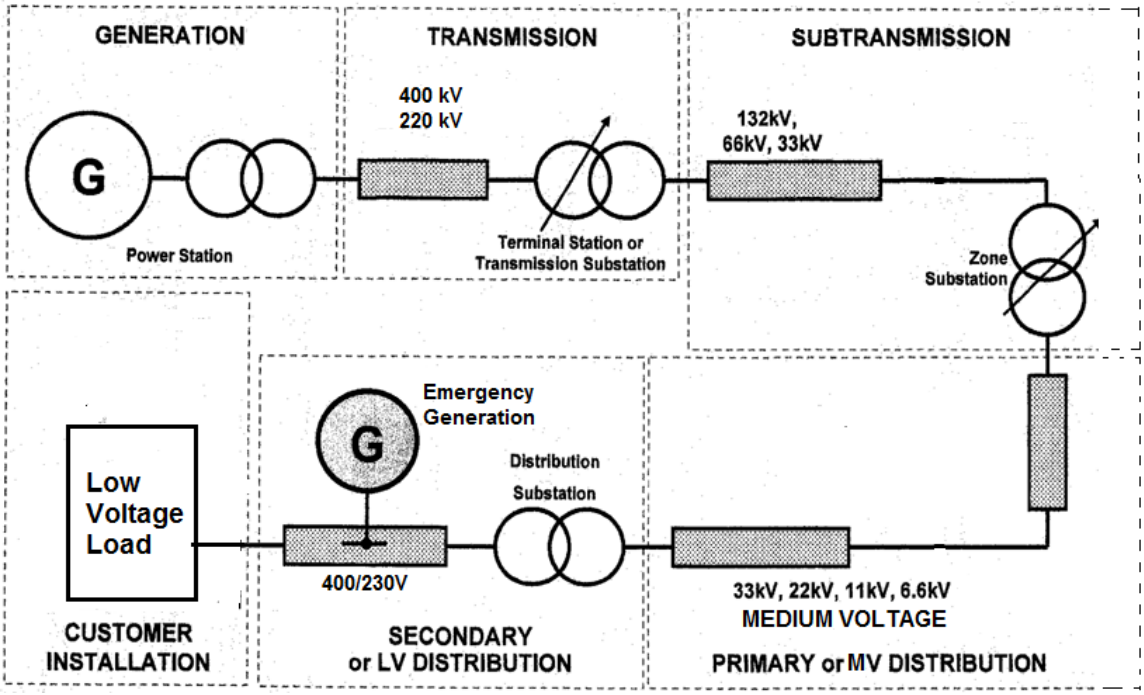
- The objectives of power system protection are to :
  — Limit the extent and duration of service interruption whenever equipment failure, human error, or adverse natural events occur on any portion of the system
  — Minimize damage to the system components involved in the failure and Prevention of human injury

- Protection engineering concerned with the design and operation of "protection schemes".

- Protection schemes are specialized control systems that monitor the power system, detecting faults or abnormal conditions and then initiate correct action.

- In this course the power system is considered as all the plant and equipment necessary to generate, transmit, distribute and utilize the electric power.

# The Construction of a Power system : Primary system




## Secondary systems in a Power system

- Protection
- Auto control for voltage, frequency, reactive power compensation, power flow, network configuration and stability
- Metering for billing, operational control and statistical data
- Local manual control (plant status, voltage level reactive power support, network configuration)
- Remote manual control via communications links (SCADA)
- Plant condition monitoring and alarming (temperature, malfunction, maintenance need, operating duty)
- Communications infrastructure
- Instrument transformers - current and voltage transformers

**Protection against faults and abnormalities**

# Types of Faults and Abnormalities

## Faults :

The principal electrical system faults are short circuits and overloads.
Short circuits may be caused in many ways, including failure of insulation due to excessive heat or moisture, mechanical damage to electrical distribution equipment, and failure of utilization equipment as a result of overloading or other abuse.
Short circuits may occur between two-phase conductors, between all phases of a poly-phase system, or between one or more phase conductors and ground. The short circuit may be solid (or bolted) or welded, in which case the short circuit is permanent and has relatively low impedance. The main types of faults in a power system are:

- **Short-circuit faults (3Φ, 2Φ, Φ g, 2 Φ g)**
- **Open-circuit faults (open conductor)**
- **Complex faults (inter-circuit, broken conductor, cross-country etc)**
- **Inter-turn faults in windings**

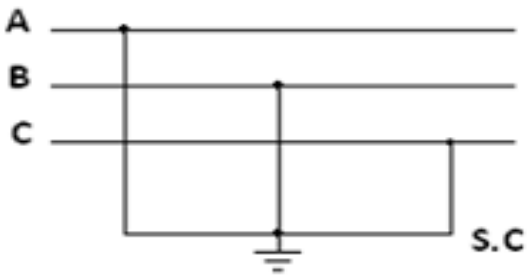
## Abnormalities:

- **Real power deficit - underfrequency**
- **Power swings**
- **Overload and excessive operating temperature**
- **Power frequency overvoltage or undervoltage**
- **Underexcitation of synchronous machines**
- **Overfluxing of power transformers**
- **Asynchronous operation of synchronous machines**
- **Overfrequency**
- **Mechanical defects i.e. leaking oil, tap changer mechanism faults .**

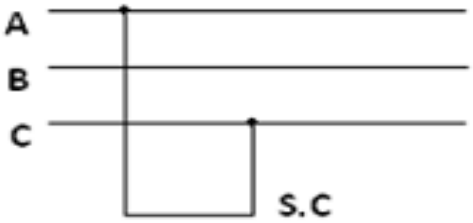
# Types of Faults

- **Short circuit type faults (solidly earth fault)**

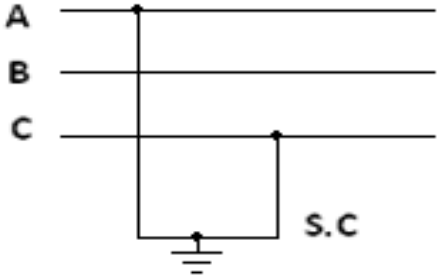
3Φ Symmetrical faults



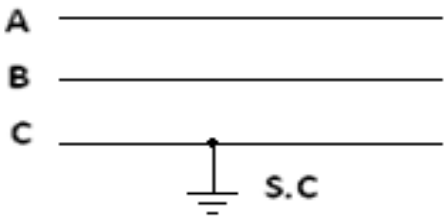

3Φ to ground faults




2Φ faults

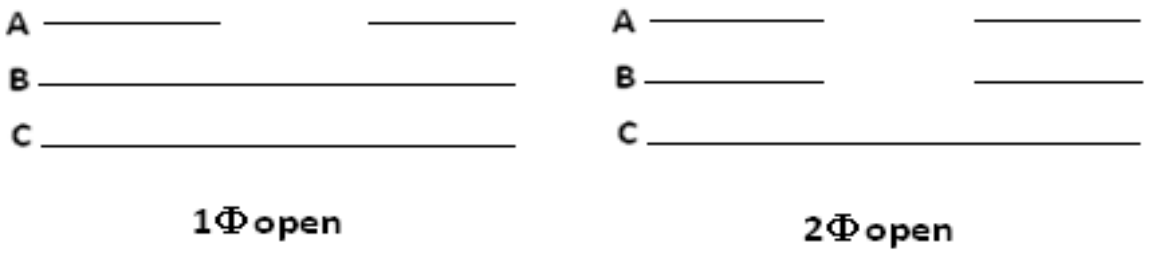



2Φ to ground faults

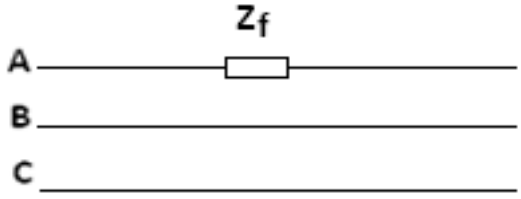



1Φ– ground faults

- **Series (Open-circuit) type faults**

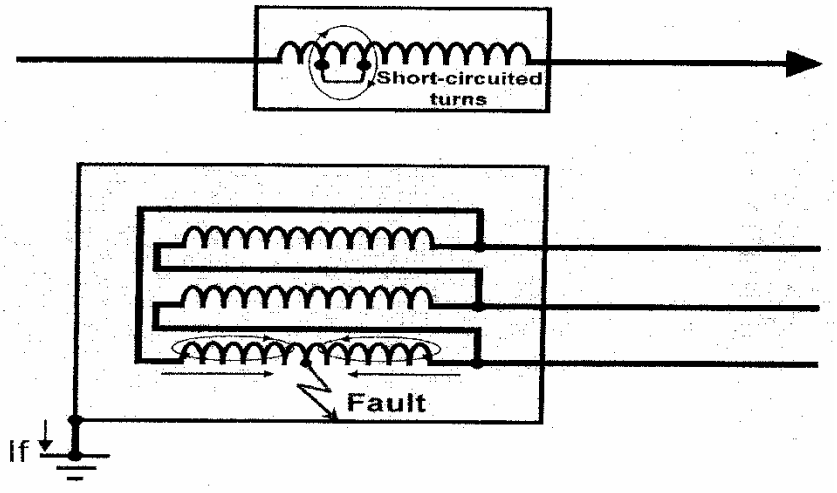



1Φ open 2Φ open




Series impedance in 1Φ

- **Faults in Windings**



## Typical Short-Circuit Type Distribution

- Single-Phase-Ground: 70 – 80 %
- Phase-Phase-Ground: 17 – 10 %
- Phase-Phase: 10 – 8 %
- Three-Phase: 3 – 2 %

## Causes of Short-Circuit Faults

- Insulation breakdown due to inherent weakness Lightning
- Birds and animals bridging insulators
- Dig-ups for underground cables
- Poles collapsing
- Conductors breaking
- Vehicle impact
- Wind borne debris
- Incorrect operation by personnel
- Etc

# Effects of Short- Circuit Type Faults

■ Large or very large currents can flow through parts of the network - thousands or tens of thousands of Amps can be involved

■ These large currents can only be allowed to flow for a very short time otherwise equipment and generators would be damaged, most likely terminally - allowable short-circuit current flow duration could range from as short as 10 milliseconds up to say 3 seconds.

■ Arcs, sparking and the heating effect of short-circuit currents can start fires involving non-electrical assets / property

■ Very large mechanical forces can be caused by short - circuit currents which have potential to break or damage equipment

■ Electric current can "escape" from the network conductors and flow through paths where they could create a hazard to people or livestock and cause damage to non-electrical assets/property

# Planning system protection

The designer of electrical power systems has available several techniques to minimize the effects of faults and abnormalities occurring on the system or in the utilization equipment that the system supplies. One can design into the electric system features that

a) Quickly isolate the affected portion of the system and, in this manner, maintain normal service for as much of the system as possible. This isolation also minimizes damage to the affected portion of the system.

b) Minimize the magnitude of the available short-circuit current and, in this manner, minimize potential damage to the system, its components, and the utilization equipment it supplies.

c) Provide alternate circuits, automatic transfers, or automatic reclosing devices, where applicable, in order to minimize the duration or the extent of supply and utilization equipment outages.

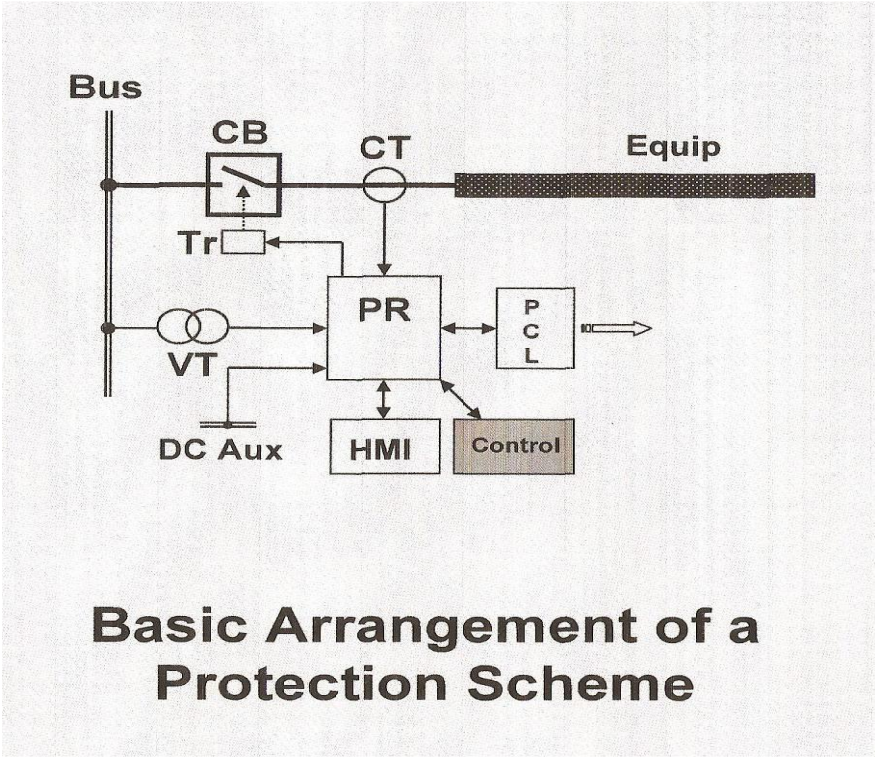
System protection encompasses all of the above techniques; however, this text deals mainly with the prompt isolation of the affected portion of the system. Accordingly, the function of system protection may be defined as the detection and prompt isolation of the affected portion of the system whenever a short-circuit or other abnormality occurs that might cause damage to, or adversely affect, the operation of any portion of the system or the load that it supplies.

# Performance Requirements of Protection System

- **Discriminate** between load (normal) and fault (abnormal) conditions
- Not be confused by non-damaging transient conditions
- Be **selective** - coordinate with other protection systems
- **Fast** enough to prevent damage and hazards - but not too fast
- Have no **"blind spots"** i.e. unprotected zones
- High degree of **reliability** and **availability**
- Secure against incorrect operation **(security)**
- Should not restrict rating of primary plant and equipment
- Should be **affordable**

# Basic Protection Scheme Components

The isolation of faults and abnormalities requires the application of protective equipment that senses when an abnormal current flow exists and then removes the affected portion from the system. The primary protective equipment components are shown in the following figure:

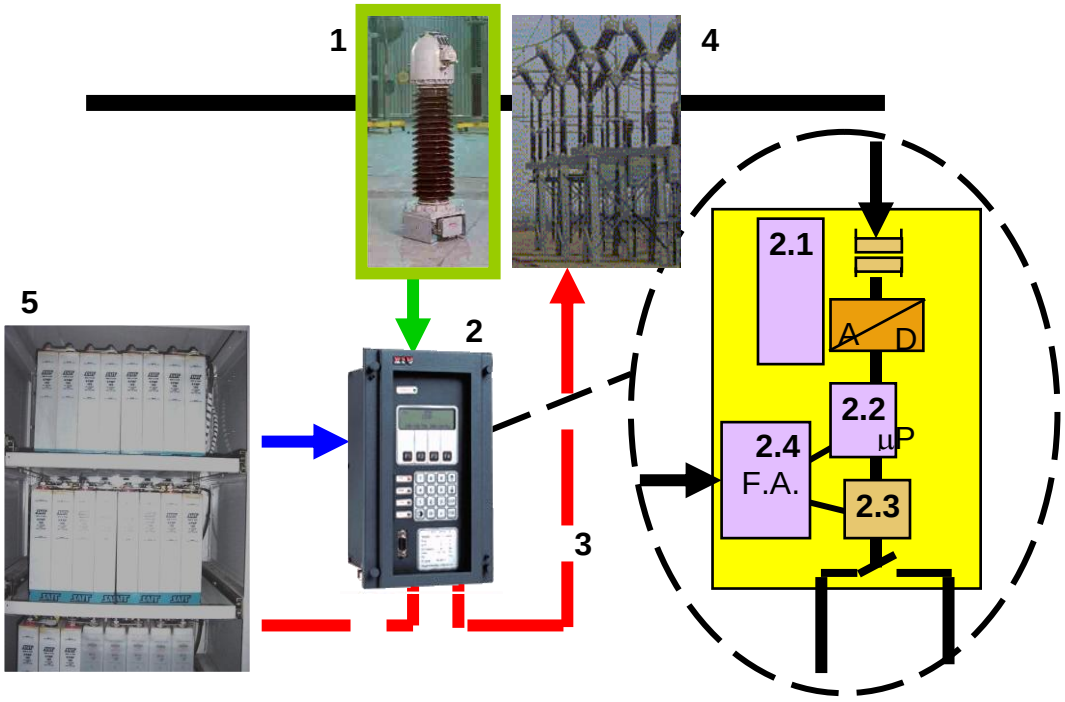



**Basic Arrangement of a Protection Scheme**

| | |
|---|---|
| **PR** | **Protection Relay** |
| **CB** | **Circuit Breaker** |
| **Equip** | **Protected Item** |
| **CT** | **Current Transformer** |
| **VT** | **Voltage Transformer** |
| **DC Aux** | **DC Auxiliary supply** |
| **HMI** | **Man-machine interface** |
| **PCL** | **Communications Link** |
| **Tr** | **CB trip coil** |

The two primary protective equipment components used in the isolation of faults and abnormalities are circuit breakers, and protective relays.

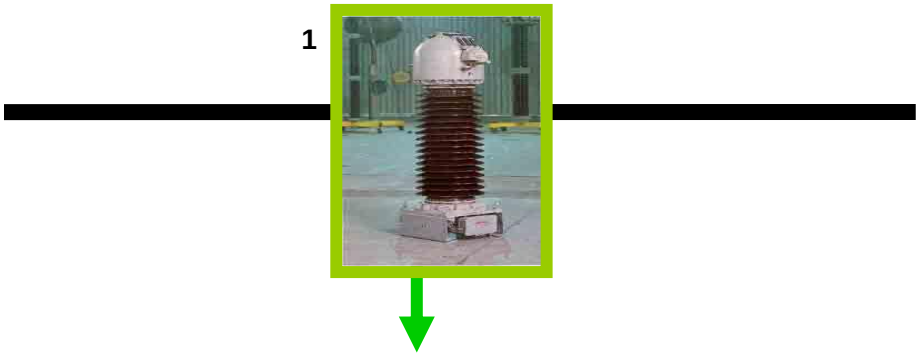
# Elements of a Protection System



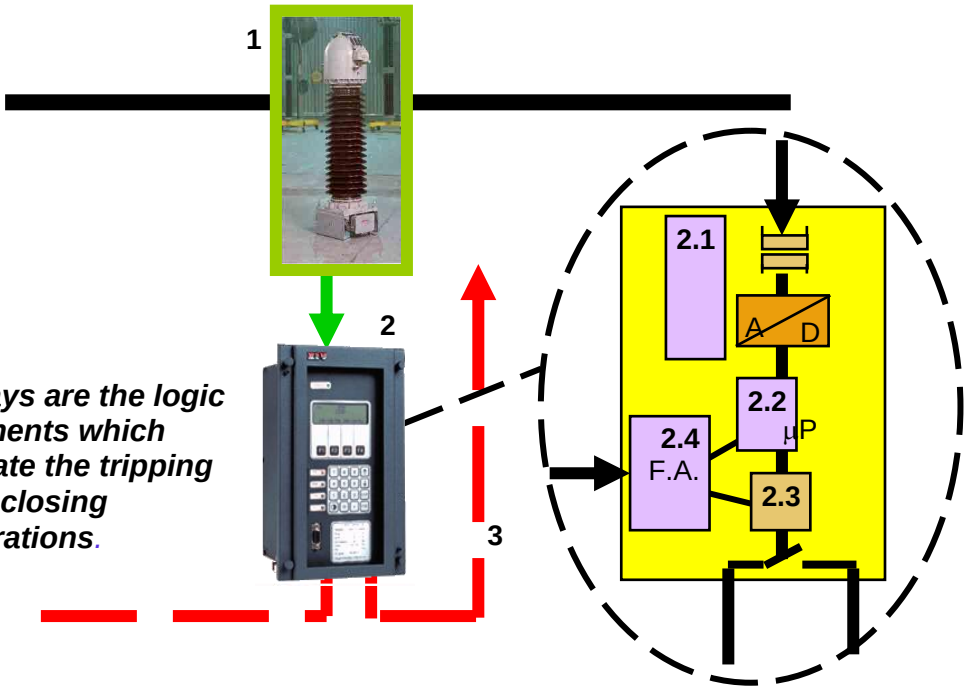

1 – CT or VT , 2- Relay 3- TC 4- CB 5- DC supply

F.A. = Fault Alarm

# Elements of a Protection System

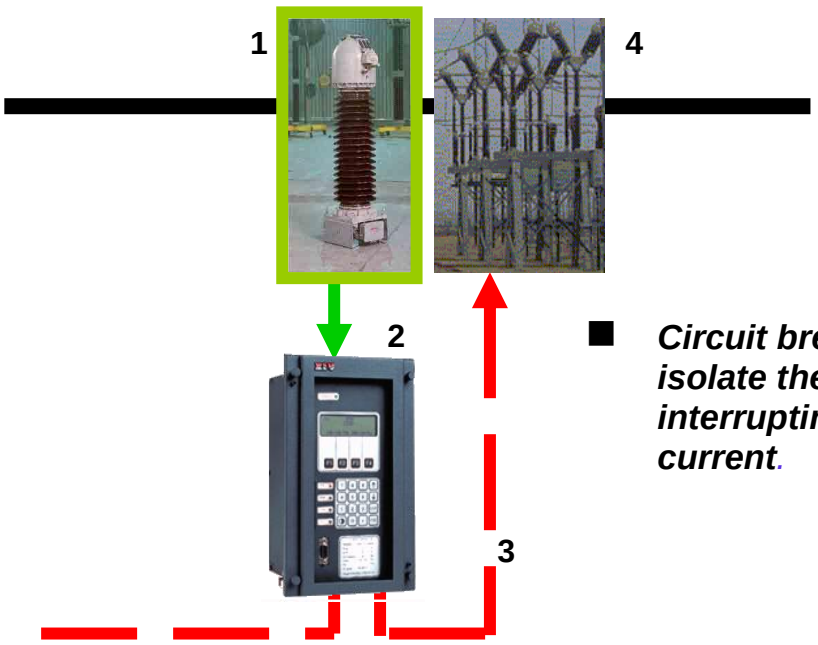



- *The function of transducers (usually CT and VT) is to provide current and voltage signals to the relays, to detect deviations of the parameters watched over.*



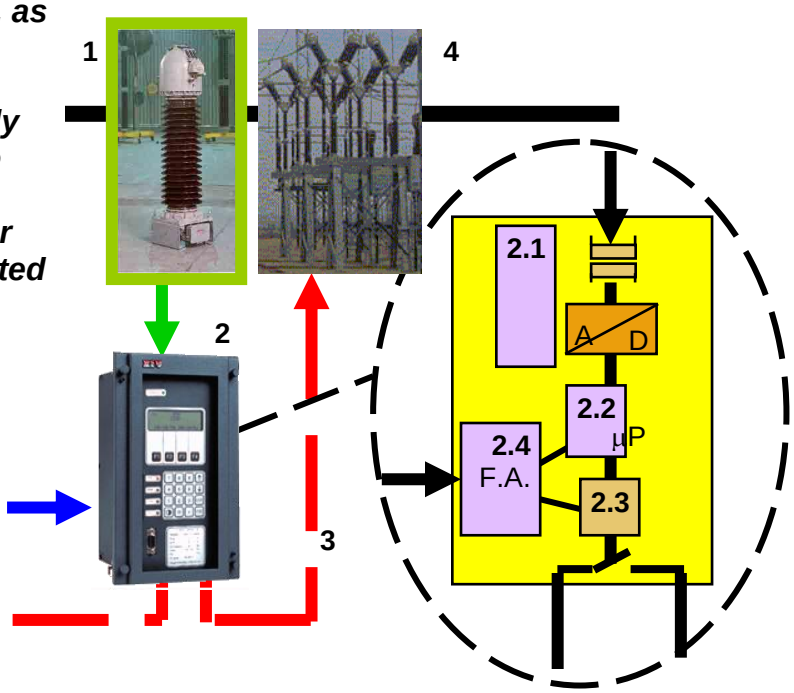

- ***Relays are the logic elements which initiate the tripping and closing operations.***

# Elements of a Protection System




- ***Circuit breakers isolate the fault by interrupting the current.***

- ***Tripping power, as well as power required by the relays, is usually provided by the station battery because is safer than the ac faulted system.***



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|---|---|
| **Protective Relays** | |

## *What is a Relay?*

- Device which receives a signal from the power system and determines whether conditions are "normal" or "abnormal" (measuring function)-
- If an abnormal condition is present, relay signals circuit breaker to disconnect equipment that could be damaged (Switching or signaling function)
- "Relays" signal from system to circuit breaker.

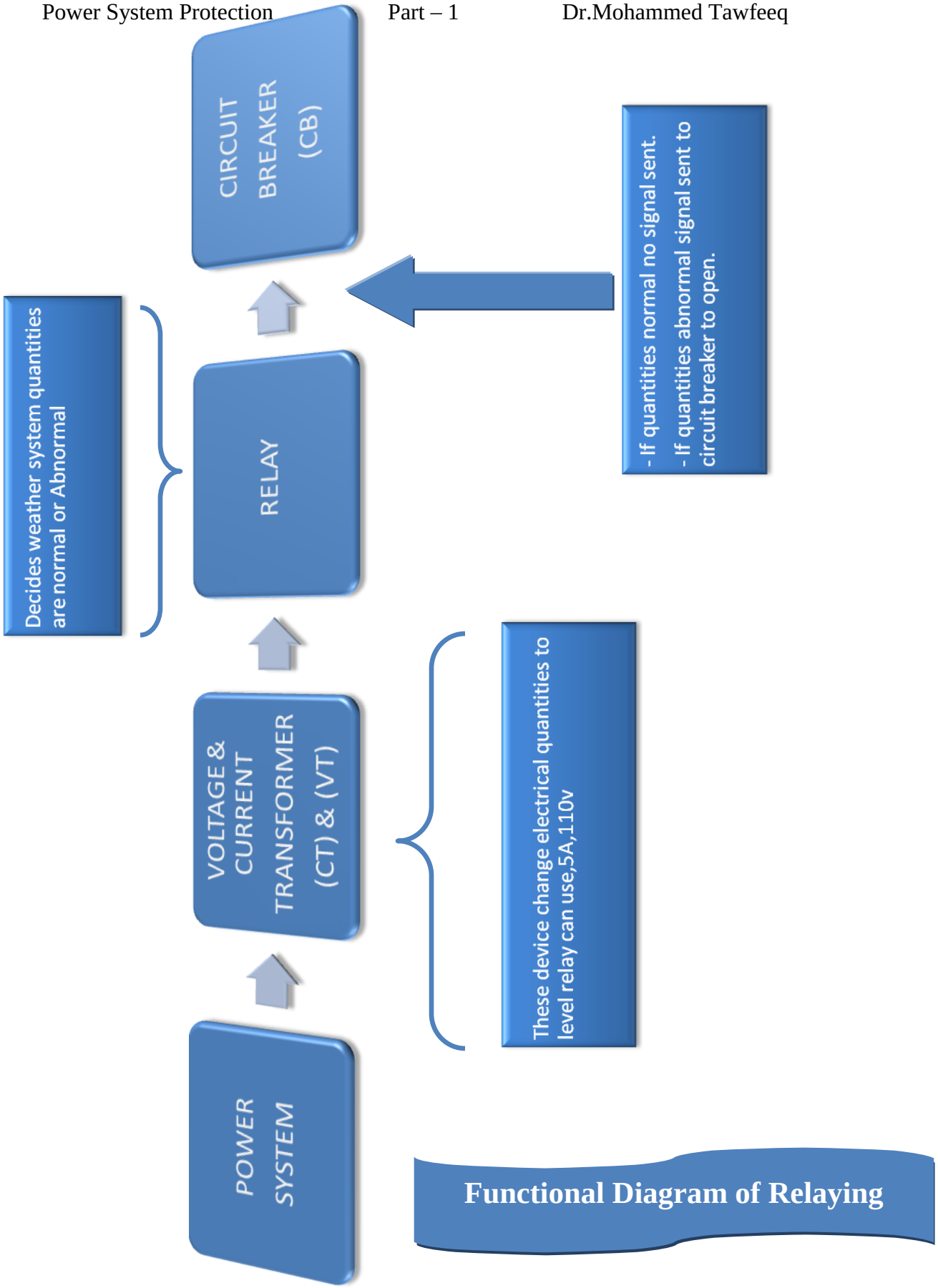
## What is the Purpose of the Relay?

The purpose of the protective relaying systems is to isolate only the faulty component of power system.

Relaying equipments are classified into two groups:

1. Primary relaying equipment.
2. Back-up relaying equipment.

Primary relaying is - the first line of defense for protecting the equipments.
Back-up protection relaying works only when the primary relaying equipment fails (they are slow in action).


POWER SYSTEM
VOLTAGE & CURRENT TRANSFORMER (CT) & (VT)
These device change electrical quantities to level relay can use,5A,110v
RELAY
Decides weather system quantities are normal or Abnormal
- If quantities normal no signal sent.
- If quantities abnormal signal sent to circuit breaker to open.
CIRCUIT BREAKER (CB)

**Functional Diagram of Relaying**

# Desirable Relay Characteristics

- **Speed** (1/60 sec)
  - * Minimizes damage from current
  - * Maximizes power transfer during normal conditions, stability
- **Security**
  - * Relay should not cause circuit breaker to open during normal conditions
- **Dependability**
  - * Relay should cause circuit breaker to open during abnormal conditions
- **Sensitivity**
  - Ability of a relay to detect all faults for the expected limiting system and fault conditions
- **Selectivity**
  - Ability of a relay system to discriminate between faults internal and external to its intended protective zones.

## Damage is Extensive When Relays Do Not Operate Correctly

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| **Classifications of Relays** | |

# Classification of Relays

Protection relays can be classified in accordance with the ***function*** which they carry out, their ***construction***, the ***incoming signal*** and the type of ***protection.***

**1.** ***General function:***

- Auxiliary.
- Protection.
- Monitoring.
- Control.

**2.** ***Construction:***

- Electromagnetic.
- Solid state.
- Microprocessor.
- Computerized.
- Nonelectric (thermal, pressure .....etc.).

***3. Incoming signal:***

- Current.
- Voltage.
- Frequency.
- Temperature.
- Pressure.
- Velocity.
- Others.

***4. Type of protection***

- **Over current.**
- **Directional over current.**
- **Distance.**
- **Over voltage.**
- **Differential.**
- **Reverse power.**
- **Other.**

# Definitions:

■ **Normally open contact ( N/O)**: is one which is open when the relay is not energized.
■ **Normally closed contact (N/C):** is one which is closed when the relay is not energized.
■ **Operating force or torque:** that which tends to close the contacts of the relay.

■ **Restrain force or torque:** that which opposes the operating force or torque and tend to prevent the closure of the relay contacts.

■ **Pick-up level:** the value of the actuating quantity (current or voltage), which is on the border above which the relay operates.

■ **Drop-out or reset level:** the value of current or voltage below which a relay opens its contacts and comes to original position..

■ **Operating time:** the time which elapses between the instant when the actuating quantity exceeds the pick-up value to the instant when the relay contacts close.

■ **Reset time:** the time which elapses between the instant when the actuating quantity becomes less than the reset value to the instant when the relay contact returns to its normal position.

■ **Primary relays:** the relays which are connected directly in the circuit to be protected.

■ **Secondary relays**: the relays which are connected in the circuit to be protected through CTs and V.Ts.

■ **Auxiliary relays:** relays which operate in response to the opening or closing of its operating circuit to assist another relay in the performance of its function. This relay may be instantaneous or may have a time delay.

■ **Reach:** a distance relay operates whenever the impedance seen by the relay is less than a prescribed value, this impedance or $_r$t]ic corresponding distance is known as the reach of the relay.
■ **Instantaneous relay**: One which has no intentional time-delay and operates in less than 0.1 second.
■ **Blocking:** preventing the protective relay from tripping cither due to its own characteristics or to an additional relay.

■ **Time delay relay :** One which is designed with a delaying means .

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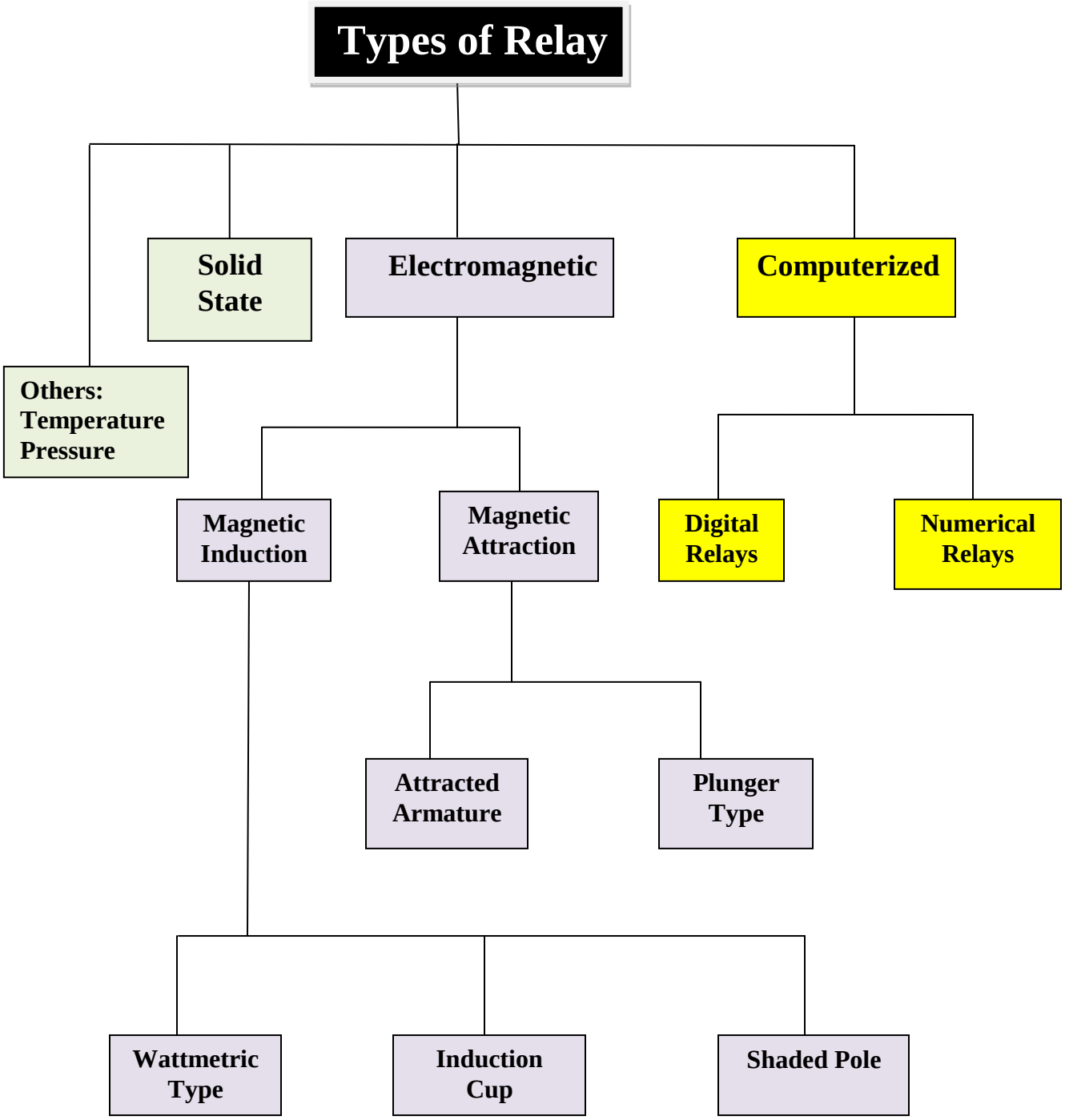
|---|---|
| Types of Relays | |

The main types of protective relays are summaries in the following diagram:



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|---|---|
| **Electromagnetic Relays** | |

**1. Electromagnetic relays**

## Electromechanical Relays

- Research Began at the End of the 19th Century
- The Relay Family Was Completed in the 1930's
- They Are Still in Use

These relays were the earliest forms of relay used for the protection of power systems, and they date back nearly 100 years. They work on the principle of a mechanical force causing operation of a relay contact in response to a stimulus. The mechanical force is generated through current flow in one or more windings on a magnetic core or cores, hence the term electromechanical relay. The principle advantage of such relays is that they provide galvanic isolation between the inputs and outputs in a simple, cheap and reliable form – therefore for simple on/off switching functions where the output contacts have to carry substantial currents, they are still used.
Electromechanical relays can be classified into several different types as follows:

**a.** magnetic attracted armature relays
**b**. magnetic induction relays
**c**. moving coil
**d.** thermal

However, only attracted armature and induction types have significant application at this time, all other types having been superseded by more modern equivalents. Electromagnetic relays are constructed with electrical, magnetic and mechanical components, have an operating coil and various contacts and are very robust, inexpensive and reliable. However they required maintenance by skilled personnel.

## *1.1. Magnetic attraction relays*

Magnetic attraction relays can be supplied by AC or DC, and operate by the movement of a piece of metal when it is attracted by the magnetic field produced by a coil. There are two main types of relay in this class.

- Attracted armature type (clapper type)
- Plunger type

1.1.1 **The attracted armature relays**: which are shown in Fig.1, consists of a bar or plate of metal which pivots when it is attracted towards the coil.

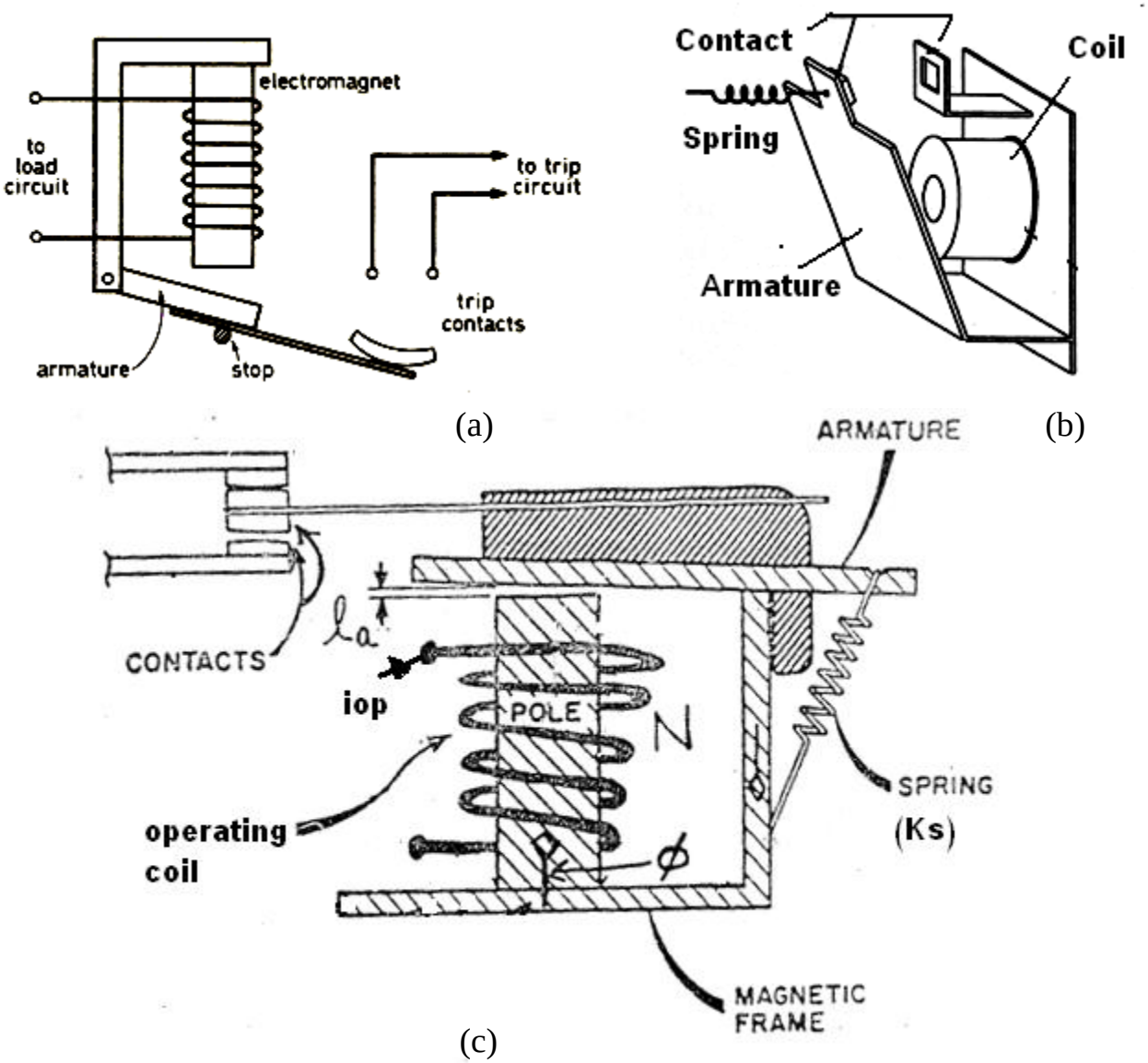



Fig. 1 Attracted armature-type relays

- The armature is attracted to the electromagnet when the current reaches a certain predetermined value ($i_{op}$ – operating current). The force of the armature will trip the link mechanism of the circuit breaker, or it may operate as a relay and close the contacts of a separate tripping circuit. The armature is attracted against gravity or a spring. By adjusting the distance of the armature from the electromagnet, or the tension of the spring, the current at which the trip operates can be varied to suit the circuit conditions.
- The armature carries the moving part of the contact, which is closed or opened according to the design when the armature is attracted to the coil.

1.1.2 **Plunger type relay:** The other type is the piston or solenoid relay, illustrated in Figure 2, in which α bar or piston is attracted axially within the field of the solenoid. In this case, the piston also carries the operating contacts. This called plunger type relay.

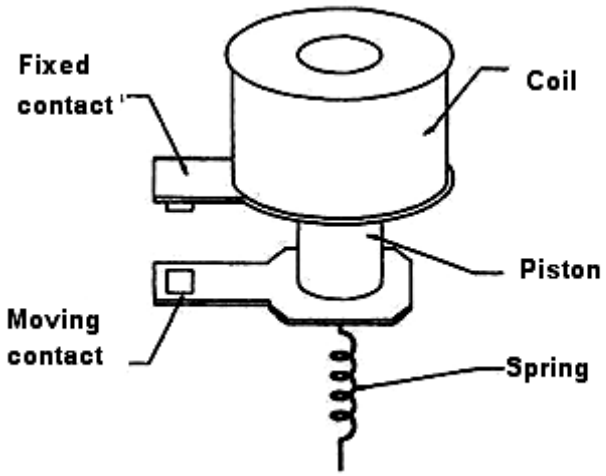



**Figure 2 Solenoid-type (plunger) relay**

- It can be shown that the force of attraction is equal to $K_1I^2$ - $K_2$, where $K_1$ depends upon the number of turns on the operating solenoid, the air gap, the effective area and the reluctance of the magnetic circuit, among other factors. K2 is the restraining force, usually produced by a spring. When the relay is balanced, the resultant force is zero and therefore $K_1 1^2 =$ K2, so that :

$$I = \sqrt{K_2 / K_1} = \text{constant.}$$

This equation can be proved as follows:

Atracted armature relay analysis

In general, the mechanical force produced by an electric magnet is propotional to $\varphi^2$; i.e:

$$F(t) \alpha \varphi^2$$

$$\varphi = \frac{mmf}{R} = \frac{N_i}{R} \quad \text{where}$$

$$R = \frac{l_g}{\mu_o A} \alpha l_g \quad = \text{reluctance}$$

So $\varphi \alpha \frac{Ni}{l_g}$ or $\varphi^2 \alpha \frac{N^2 i^2}{l_g^2}$

Hence $F(t) = k_\varphi \varphi^2$ Where $k_\varphi$ is constant

$$= k_\varphi \frac{N^2 i^2}{l_g^2} = k_1 i^2 \qquad , k_1 = k_\varphi \frac{N^2}{l_g^2}$$

The net force is

$$F_n(t) = F(t) - k_2 = k_1 i^2 - k_2$$

Where $k_2 =$ restraining force produced by the spring

When the relay is balanced $F_n(t) = 0$

$$O = k_1 I^2 - k_2$$

So $k_1 I^2 = k_2$

or $I = \sqrt{\frac{k_2}{k_1}} =$ constant

$I$ = RMS value of $i$

- In order to control the value at which the relay starts to operate, the restraining tension of the spring or the resistance of the solenoid circuit can be varied, thus modifying the restricting force. *Attraction relays effectively have no time delay and, for that reason, are widely used when instantaneous operations are required.*

Example :
An electromagnetic relay of attracted armature type has constants $k_1 = 0.6$ and $k_2 = 10$ find whether the relay will operate or not when:

(a) A current of 4A flows through the relay winding.

(b) A current of 5A flows through the relay winding.

(c) Find the minimum current required to operate the relay.

Solution:

(a) For 4A current:

$$F_n(t) = k_1 I^2 - k_2 = 0.6(4)^2 - 10 = -0.4N$$

So the relay will not operate. Since, the restrain force > operating force.

(b) For 5A current:

$$F_n(t) = k_1 I^2 - k_2 = 0.6(5)^2 - 10 = 15 - 10 = 5N$$

Hence, the relay will operate, since, the operating force > restrain force

(c) The minimum current required to operate the relay is when the relay becomes at balanced condition, i.e $F_n(t) = 0$

or $$I = \sqrt{\frac{k_2}{k_1}} = \sqrt{\frac{10}{0.6}} = 4.08A$$

## 1.2. Magnetic induction relays

An induction relay works only with alternating current. Induction relays can be grouped into three classes as set out below.

### 1.2.1. Wattmetric-type relay

It consists of an electromagnetic system consists of two electromagnets constructed as shown in Fig.4, which operates on a moving conductor, in the form of a disc.

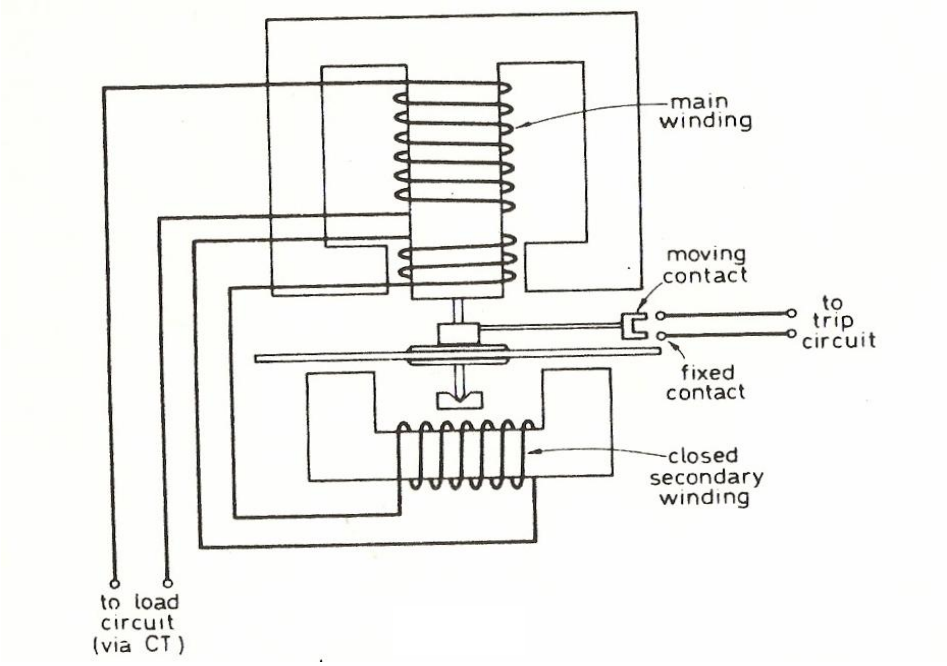



**Fig.4. Induction type overload relay**

# Electromagnetic Induction Principle

- Induction type relay: General operating principle:

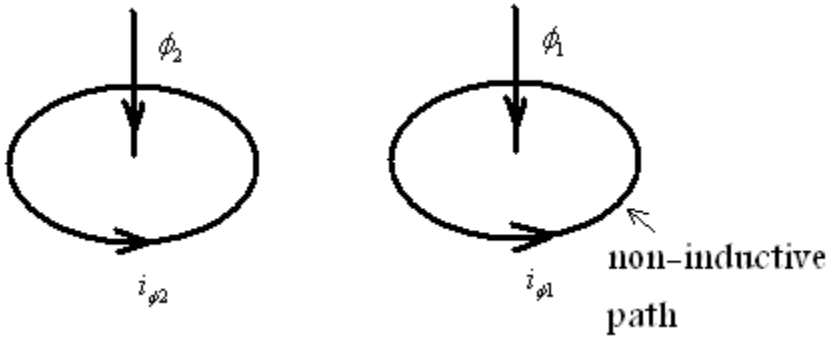
The two magnets of the induction type relay produce two alternating magnetic fields $\varphi_1$ & $\varphi_2$ :

$$\varphi_1 = \varphi_{1m} \sin \omega t$$
$$\varphi_2 = \varphi_{2m} \sin(\omega t + \theta)$$

where $\varphi_2$ leads $\varphi_1$ by an angle $\theta$.

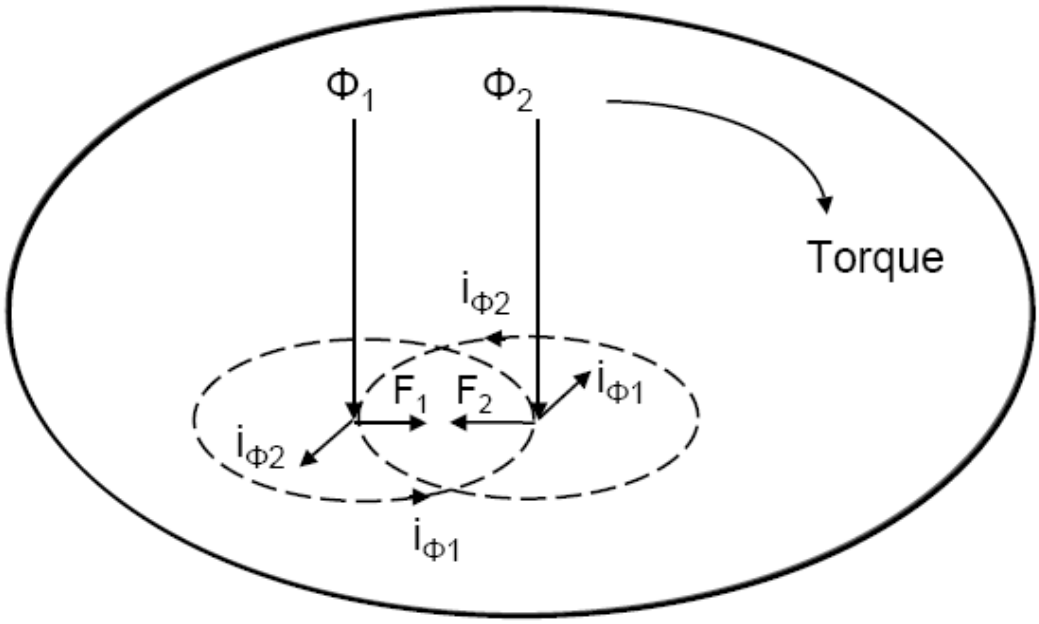
$\varphi_1$ & $\varphi_2$ produce eddy currents in the rotating disc which are $i_{\varphi 1}$ and $i_{\varphi 2}$

$$i_{\varphi 1} \alpha \frac{d\varphi_1}{d_t}$$
$$i_{\varphi 2} \alpha \frac{d\varphi_2}{dt}$$




or

$$i_{\varphi 1} \alpha \varphi_{1m} \cos \omega t$$
$$i_{\varphi 2} \alpha \varphi_{2m} \cos(\omega t + \theta)$$




$F_1$ is the force produced by intersection of $\varphi_1$ and $i_{\varphi 2}$.

$F_2$ is the force produced by intersection of $\varphi_2$ and $i_{\varphi 1}$.

The net force is

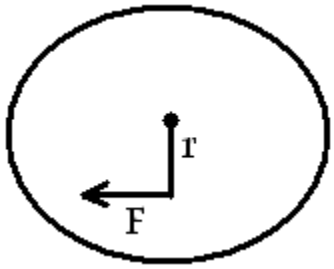
$$F = F_2 - F_1 \alpha [\varphi_2 i_{\varphi 1} - \varphi_1 i_{\varphi 2}]$$

Thus $F \alpha \varphi_{1m} \varphi_{2m} [\sin(\omega t + \theta) \cos \omega t - \sin \omega t \cos(\omega t + \theta)]$

Now $\sin(\omega t + \theta) \cos \omega t = \sin \omega t \cos \omega t \cos \theta + \sin \theta \cos^2 \omega t$

$$-\sin \omega t \cos(\omega t + \theta) = -\sin \omega t \cos \omega t \cos \theta + \sin^2 \omega t \sin \theta$$

$$= \sin \theta (\cos^2 \omega t + \sin^2 \omega t) = \sin \theta$$




Hence $F \alpha \varphi_{1m} \varphi_{2m} \sin \theta$

The net torque produced

$$T = Fr \alpha F$$

or

$$T = K_1 \varphi_{1m} \varphi_{2m} \sin \theta$$

Let $\Phi_1$ is the R.M.S value of $\varphi_1$, $\Phi_2$ is the R.M.S value of $\varphi_2$

So

$$F \alpha \Phi_1 \Phi_2 \sin \theta$$

or

$$T \alpha \Phi_1 \Phi_2 \sin \theta$$

In terms of currents:

$$T \alpha I_1 I_2 \sin \theta$$

or

$$T = K_t I_1 I_2 \sin \theta$$

- **Induction Type Relay with plug settings**

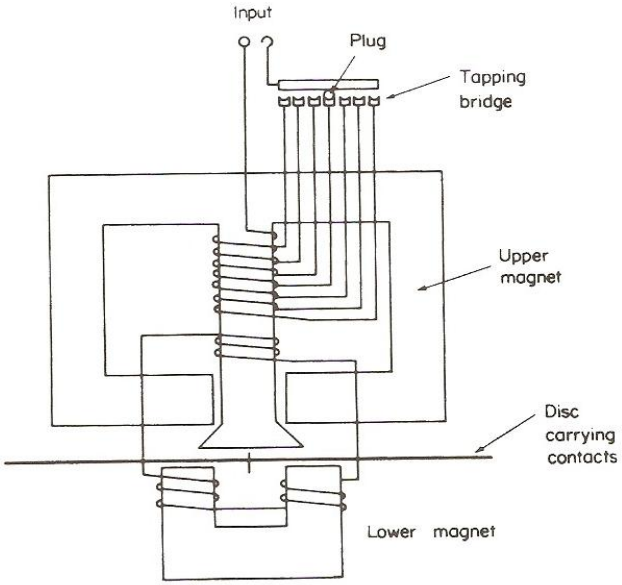



Fig.6 Induction type relay with

Plug settings

### 1.2.2. Induction-Cup relay

The operation is similar to the induction disc; here, two fluxes at right angles induce eddy currents in a bell-shaped cup which rotates and carries the moving contacts. A four-pole relay is shown in Figure 7.

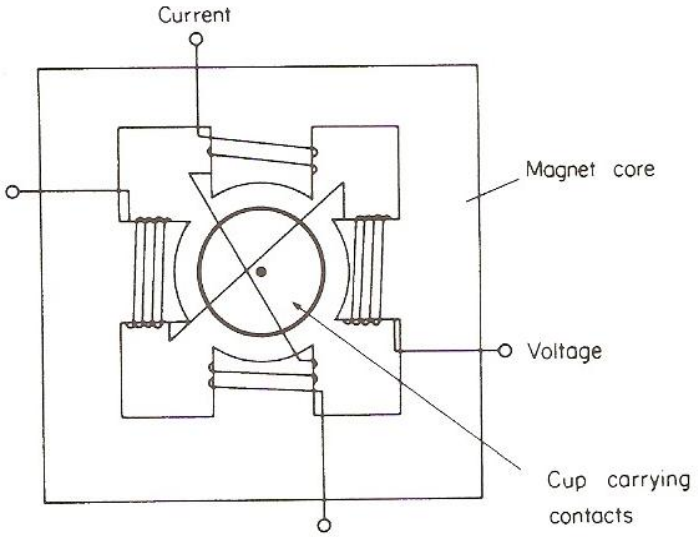



Fig 7.Four-pole induction-cup relay.

### 1.2.3. Shaded-pole relay

In this case operation of the electromagnetic section is short-circuited by means of a copper ring or coil. This creates a flux in the area influenced by the short circuited section (the so-called shaded section) which lags the flux in the nonshaded section, see Figure 8.

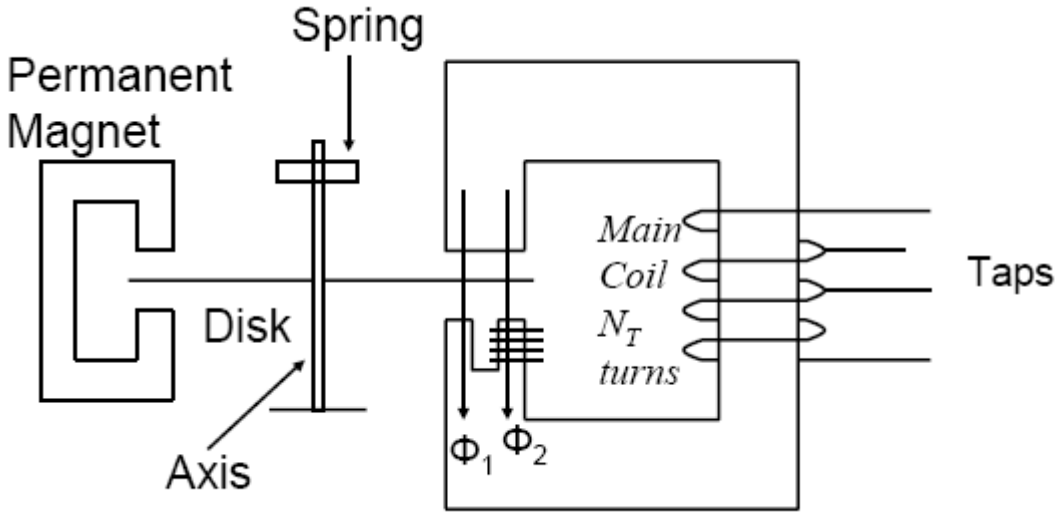



Fig.8 Shaded – pole Relay

- **Note that the main coils has TAPS, this means that the number of turns is actually adjustable.**

In the electromagnetic induction principle, the relay element has a non-magnetic rotor (an aluminum or copper disc or cylinder) in which coils create magnetic fluxes that induce circulating currents. The interaction between the fluxes and the circulating currents generates torque. This is the operation principle of induction motors.

If the current is sinusoidal and the iron core is assumed to have a linear behavior, the magnetic field and the magnetic flux in the iron core are sinusoidal too. Note that the flux is divided in two parts. One flows through the normal (‘pole”) and the other flows through the shaded pole. These two fluxes are similar in magnitude but different in angle.

# Features of the Induction Principle

- Suitable for AC Systems
- The Torque Does Not Vary With Time: No Vibration
- Inherent Rejection of DC Offset: Low Overreach

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|---|---|
| Solid State Relays | |

# 2. Solid State Relays

- Research Began in the 1940's
- First Commercial Products in the Late 1950's
- Full Development in the 1960's
- Advantages Over Electromechanical Relays

A **solid state relay (SSR)** is a solid state electronic component that provides a similar function to an electromechanical relay but does not have any moving components, increasing long-term reliability. Introduction of static relays began in the early 1960's. Their design is based on the use of analogue electronic devices instead of coils and magnets to create the relay characteristic. Early versions used discrete devices such as transistors and diodes in conjunction with resistors, capacitors, inductors, etc., but advances in electronics enabled the use of linear and digital integrated circuits in later versions for signal processing and implementation of logic functions.. Figure 9 shows a small overcurrent relay and the circuit board for a simple static relay.

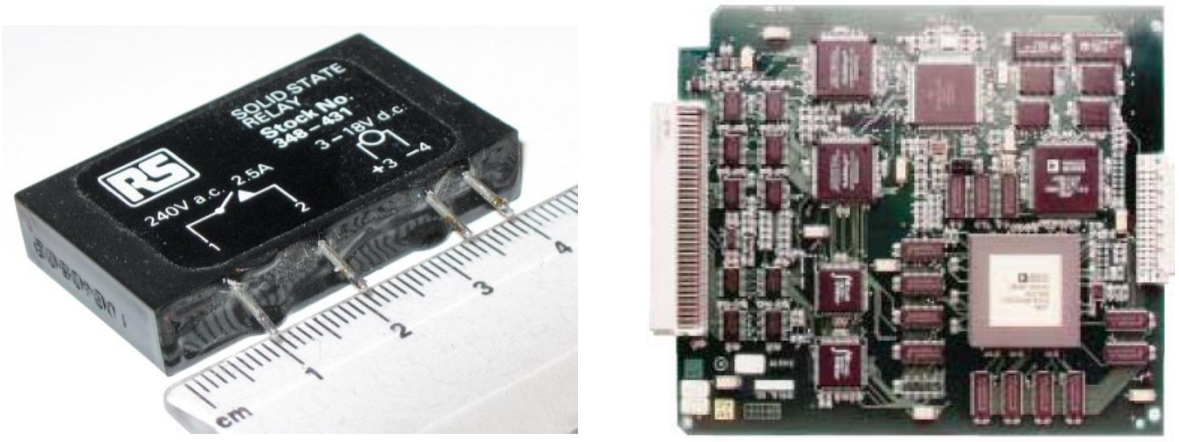


Fig.9 . Small overcurrent relay and the circuit board for a simple static relay.

# Solid State Relay Principle of Operation

Solid state relays (static relays) are extremely fast in their operation. They have no moving parts and have very quick response time and they are very reliable.
Figure 1 shows the elements used in a single – phase time lag overcurrent relay.

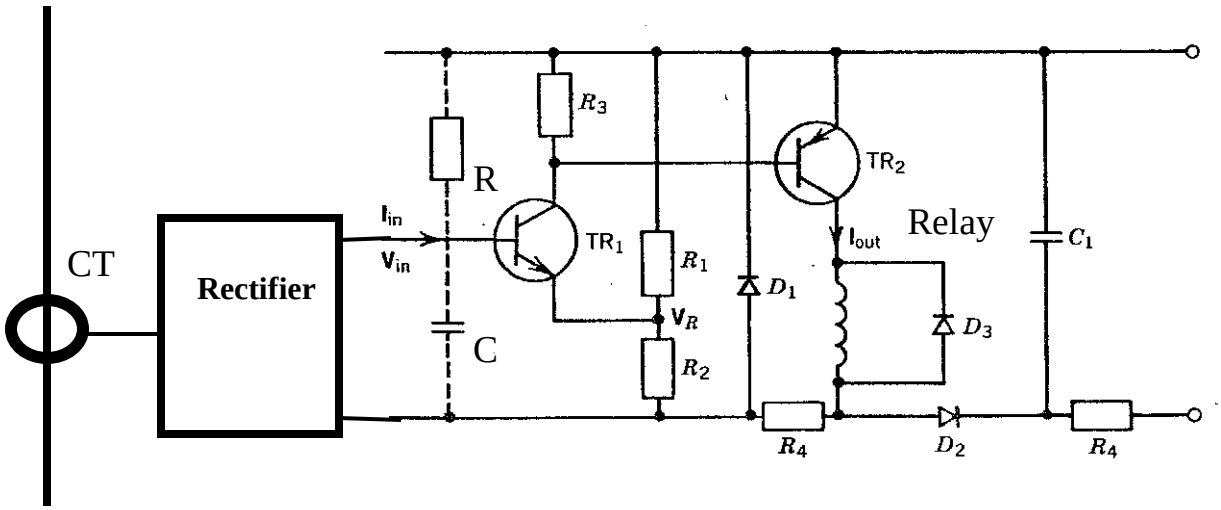


Fig.1

- The AC input from the current transformer CT is rectified and converted to DC voltage $V_{in}$ through shunt resistance.
- A delay time circuit (RC) is used to produce the required time delay.
- If $V_{in} < V_R$, the base – emitter of transistor $TR_1$ is reversed bias forcing the transistor to be in the cut off state.
- When $V_{in} > V_R$, transistor $TR_1$ will be in the ON state and in turn will turn on $TR_2$ and the output relay is activated.
- $V_R$ is set by $R_1$ and $R_2$.

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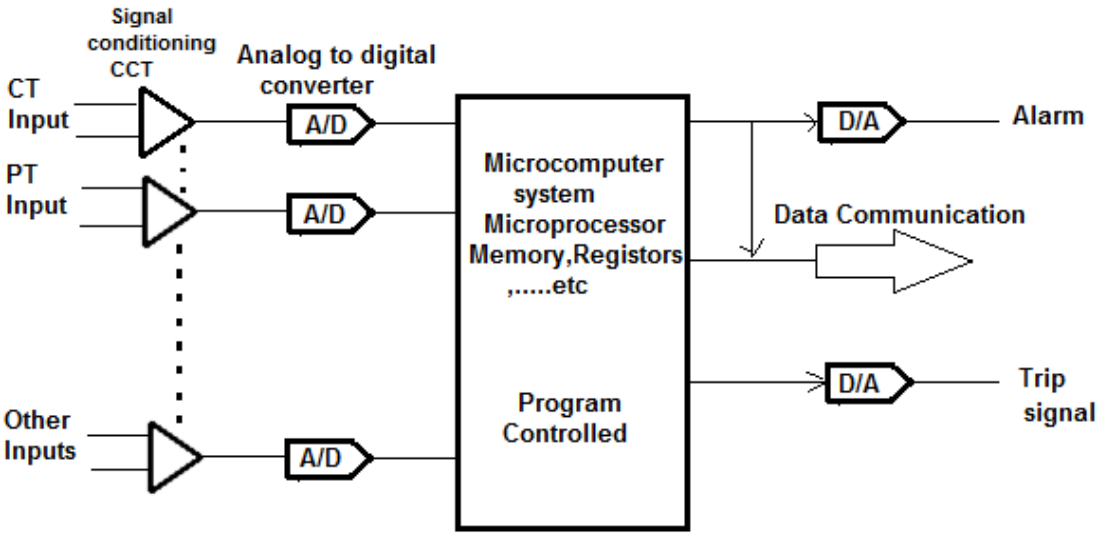
|---|---|
| Computerized Relays | |

# 3. Computerized Relay

## 3.1. Digital relays

- **Research Began in the 1960's**
- **Basic Developments: Early 1970's**
- **A Technical and Economic Solution: the Microprocessor**
- **Commercial Relays: Early 1980**

A **digital protective relay** is a microcomputer controlled relay. The data acquisition system collects the transducers information and converts it to the proper form for use by the microcomputer. Information from CT and PT and other systems is amplified and sampled at several kHz. The sampled signals are digitized with A/D converter and fed to registers in microprocessor system. The microprocessor may use some kind of counting technique, or use the Discrete Fourier Transform (DFT) to compare the information with preset limits for overcurrent , over/under voltage…etc, and then send command through D/A converter to alarm or trip signals to the circuit breakers.




Microcomputer - controlled relay

**Operation :**

- The relay applies A/D (analog/digital) conversion processes to the incoming the voltages and currents.
- The relay analyzes the A/D converter output to extract the magnitude of the incoming quantity (RMS value) using Fourier transform concept. Further, the Fourier transform is commonly used to extract the signal's phase angle relative to some reference.
- The digital relay is capable of analyzing whether the relay should trip or restrain from tripping based on current and/or voltage magnitude (and angle in some applications).

Examples of digital relays are shown in Figure 10.

Fig.10 Digital relays

# Signal Path for Microprocessor Relays

The signal path for voltage and current input signals are shown in Fig.11.

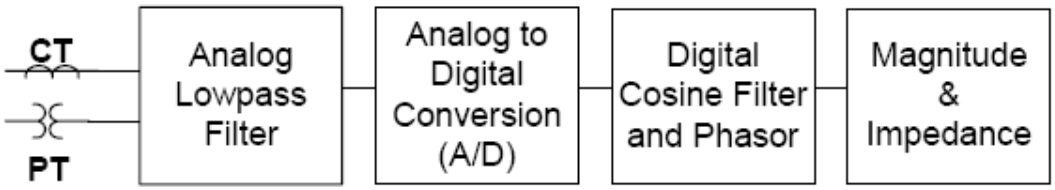



Fig.11

- After the currents and voltages are reduced to acceptable levels by the instrument transformers, the signals are filtered with an analog filter
- The signal then digitized and re-filtered with a digital filter.
- Numerical operating quantities are then calculated from the processed waveforms.

## Digital Relay Construction

- Analog Input Subsystem
- Discrete Input Subsystem
  A/D Converter
- Microprocessor
- Discrete output Subsystem
- Operating signaling and communication subsystems

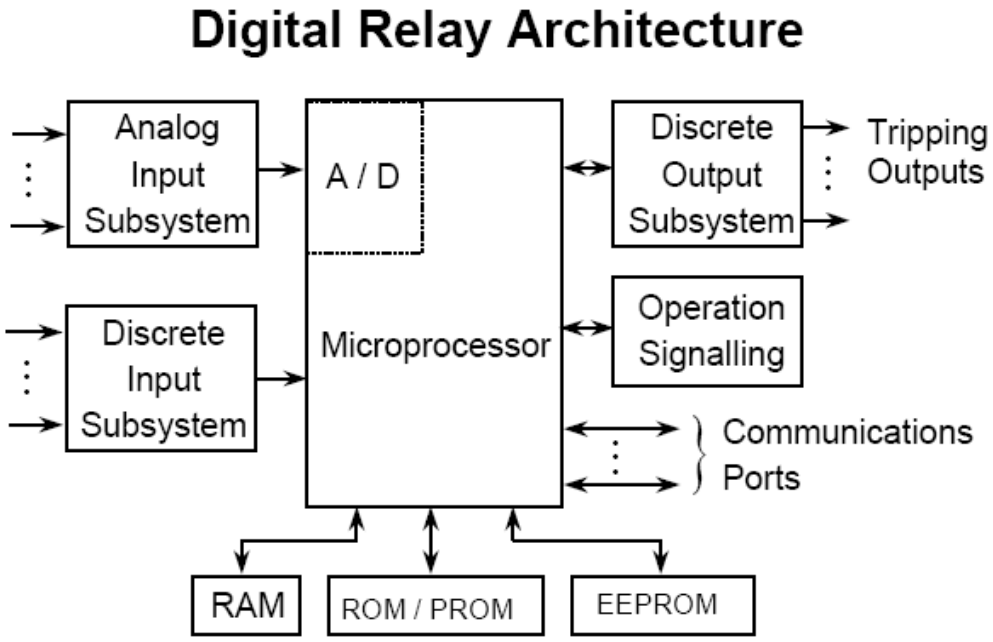
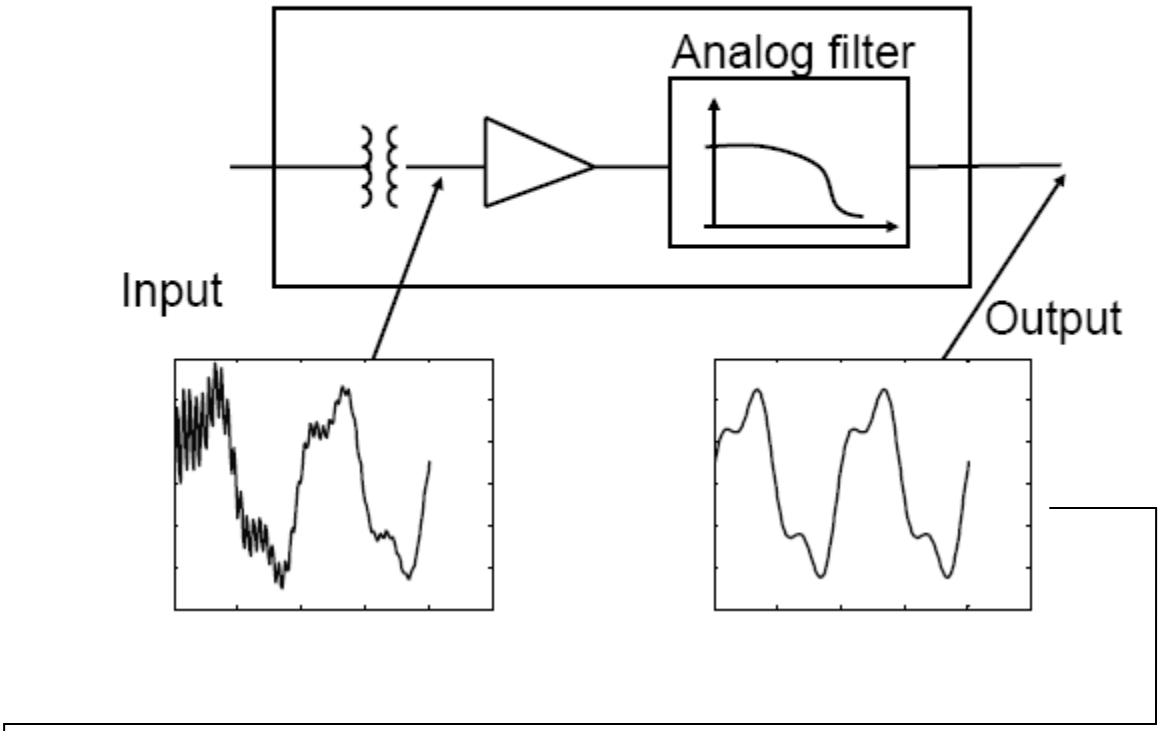
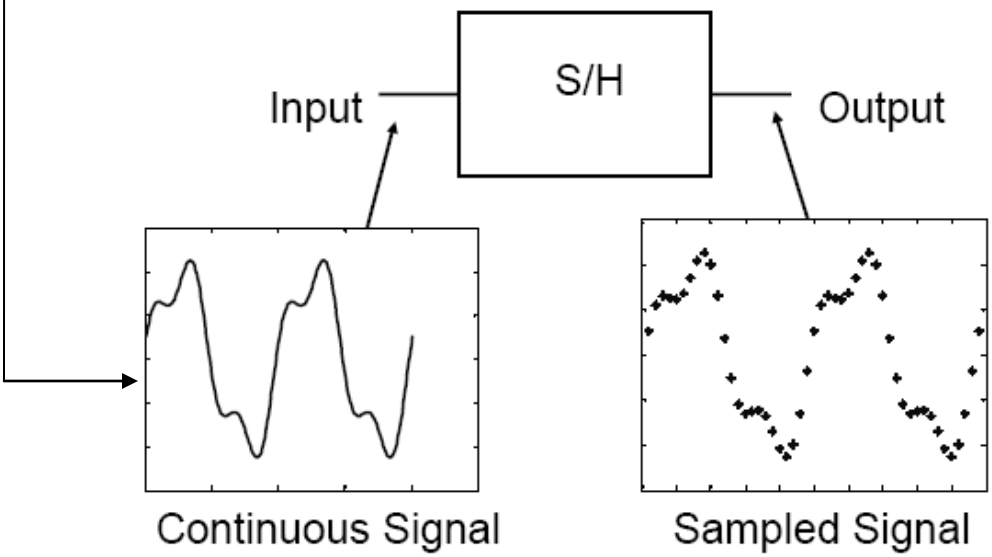



Fig.12

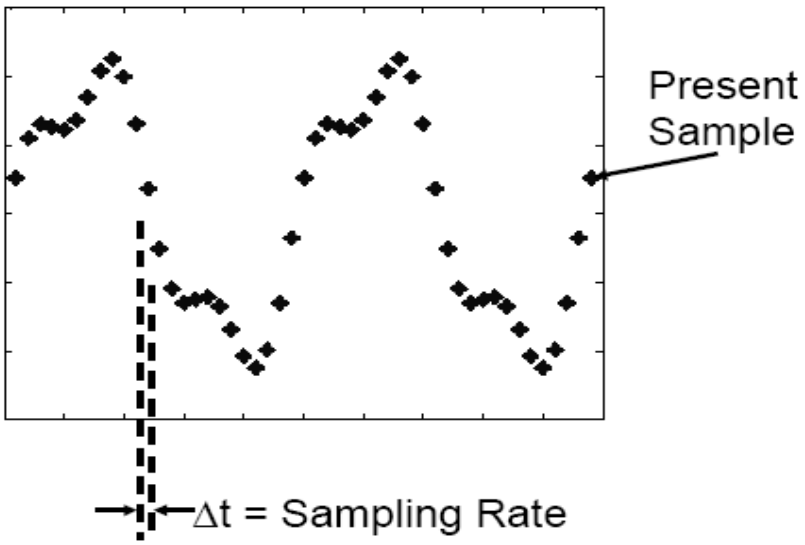
## Analog Input System




## Sampling of Analog Signals

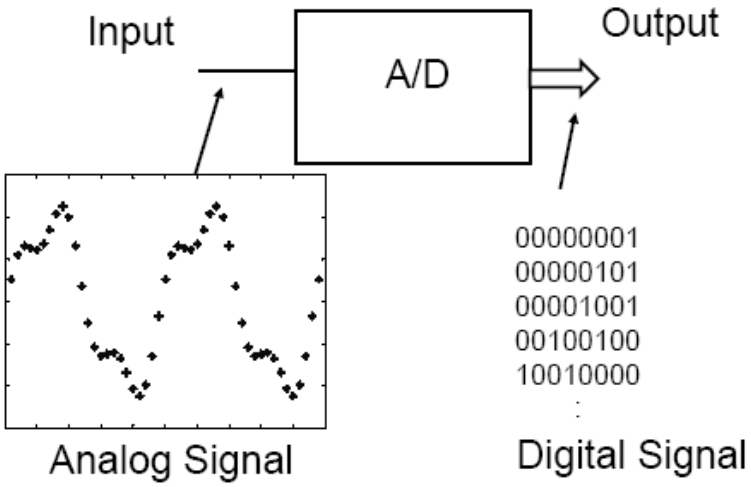


## Sampled Signal

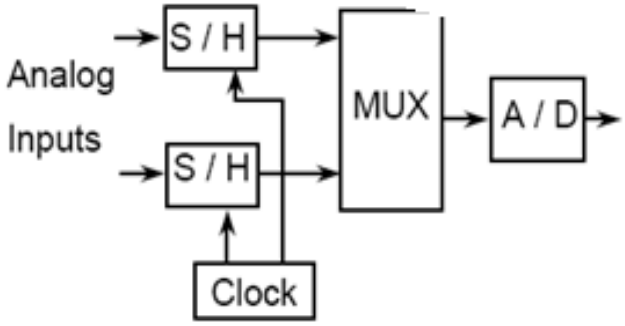



Sampling frequency is the inverse of sampling rate.

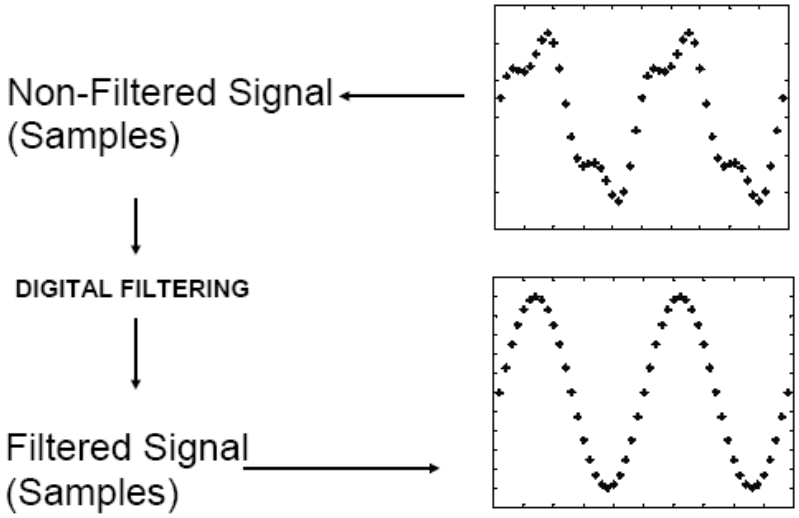
## Analog to Digital (A/D) Conversion



## Sampling and Hold system

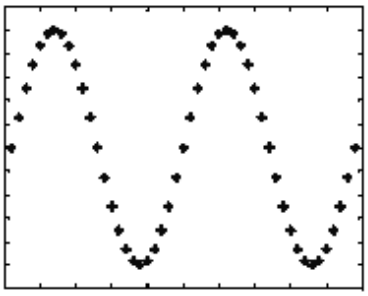



## Digital Filtering




The digital filter smoothes the signal by eliminating DC and frequencies components those are different than the fundamental (when required).

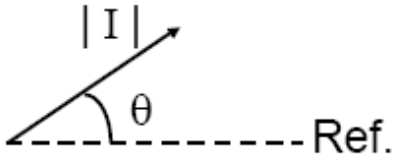
# Phasor Calculation



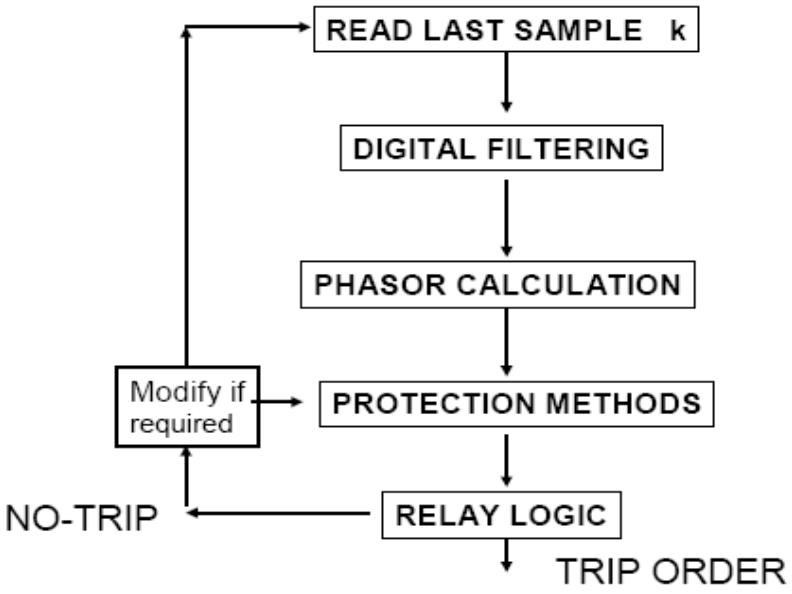
Filtered Signal (Samples)

PHASOR CALCULATION

Phasor Samples: Magnitude and Angle vs. Reference




# Digital Relay Algorithm



# Digital Relay Algorithm

The relay algorithm is a set of mathematical operations implemented in a program. These operations are performed over the last N samples of the sampled input signal. The relay makes the decision of tripping (or not) the circuit breaker based on the result of this algorithm. The algorithm presented in the slide is a particular example. The routines are:

• Reading Routines (Read last sample). This part of the program is in charge of reading the last sample of the input signals.

• Routines for Digital Filtering. The digital filter smoothes the signal, by eliminating DC and frequencies components different than the fundamental (when required).

• Routines for Phasor Calculation. These routines determine phasors V and I from the samples of the sampled signals.

• Routines for Protection Methods. These routines implement the protection function: overcurrent, directional, distance, differential, etc.

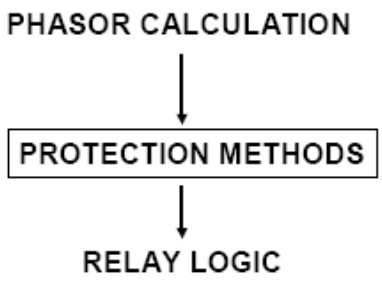
• Routines for Relay Logic. With the results of the protection methods routines, the relay logics make the final decisions for tripping and other relay functions. In some modern relays, the logic can be programmed by the user.

Sometimes the digital filtering routines and the phasor calculation routines are considered the same module.

These routines determine phasors V and I from the samples of the signals.

# Protection Methods

- Overcurrent (50, 51)
- Voltage (59, 27)
- Directional (67)
- Distance (21)
- Differential (87)
- Frequency (81)




These routines implement the protection function: overcurrent, directional, distance,differential, etc.

## Other Features :

- The relay has some form of advanced event recording. The event recording would include some means for the user to see the timing of key logic decisions, relay I/O (input/output) changes, and see in an oscillographic fashion at least the fundamental frequency component of the incoming AC waveform.
- The relay has an extensive collection of settings, beyond what can be entered via front panel knobs and dials, and these settings are transferred to the relay via an interface with a PC (personal computer), and this same PC interface is used to collect event reports from the relay.
- The more modern versions of the digital relay will contain advanced metering and communication protocol ports, allowing the relay to become a focal point in a SCADA system.

## Advantages of Digital Relays

- Low Cost
- Multifunctionality
- Protection and control
- Measurement
- Fault recording
- Communications capability
- Compatibility with Digital Integrated Systems
- High Reliability
- Relays (integration, self-testing)
- Protection system (supervised by the relays)
- Sensitivity and Selectivity
- New Protection Principles
- New Relay Operating Characteristics
- Maintenance-Free
- Reduced Burden on CTs and VTs
- Adaptive Protection

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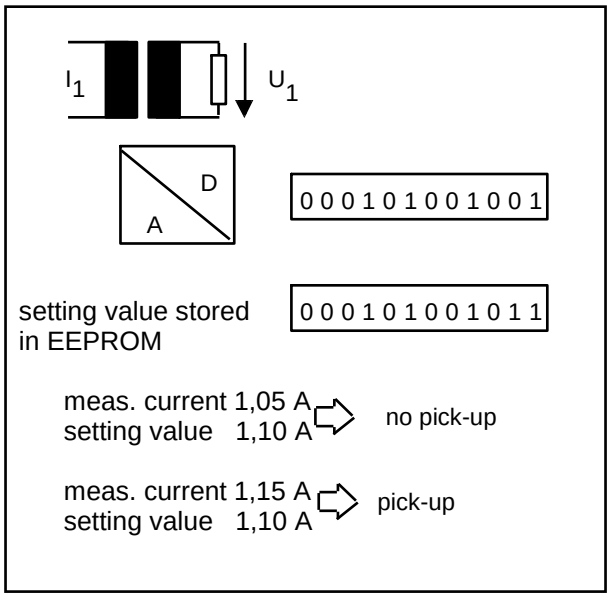
| Numerical Relays | |

## 3.2. NUMERICAL RELAYS

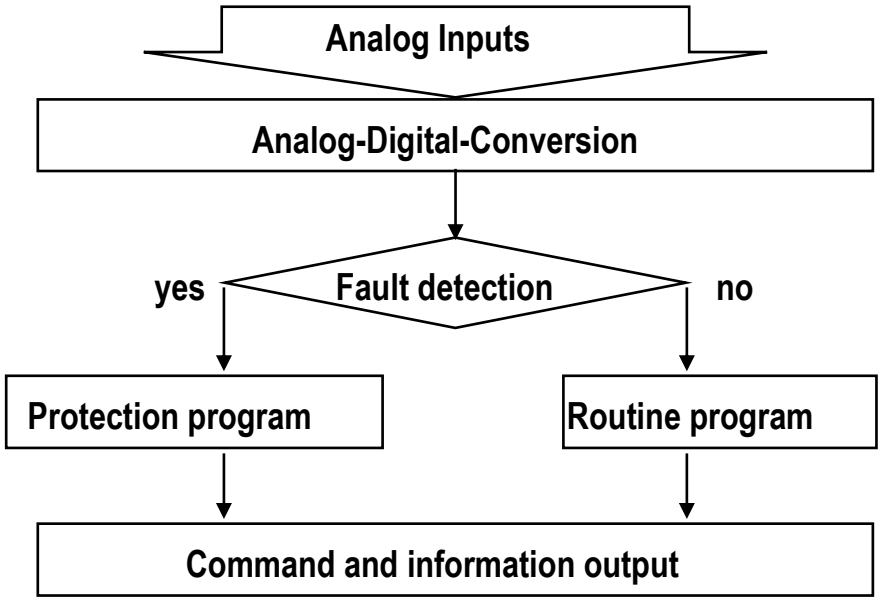
The distinction between digital and numerical relay rests on points of fine technical detail, and is rarely found in areas other than Protection. They can be viewed as natural developments of digital relays as a result of advances in technology. Typically, they use a specialized digital signal processor (DSP) as the computational hardware, together with the associated software tools.

### Numerical measurement treatment


I1
U1
D
A
0 0 0 1 0 1 0 0 1 0 0 1
setting value stored in EEPROM
0 0 0 1 0 1 0 0 1 0 1 1
meas. current 1,05 A
setting value 1,10 A
no pick-up
meas. current 1,15 A
setting value 1,10 A
pick-up

numerically the measurement value is converted into a logical digit and then compared with another digit stored in a memory

## Mode of operation




## Advantages of numerical technology

- **Comprehensive information supply**
- **clear representation of the fault sequence**

**Fault sequence of event and disturbance recording indicate**

- **What actually happened ?**
- **What did the current and voltage signals look like (CT saturation) ?**
- **When did the protection issue a trip signal ?**
- **How long did the circuit breaker need to operate ?**
- **What was the magnitude of the interrupted current ?**
- **How did the system behave after the circuit breaker tripped ?**

# ANSI Device Numbers

The **ANSI Standard Device Numbers** denote what features a protective device supports (such as a relay or circuit breaker). These types of devices protect electrical systems and components from damage when an unwanted event occurs, such as a electrical fault.

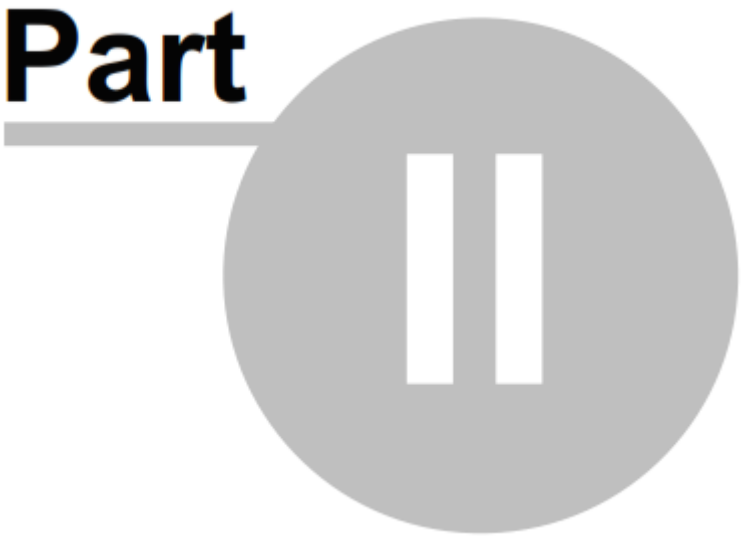
## *List of Device Numbers*

- 1 - Master Element
- 2 - Time Delay Starting or Closing Relay
- 3 - Checking or Interlocking Relay
- 4 - Master Contactor
- 5 - Stopping Device
- 6 - Starting Circuit Breaker
- 7 - Anode Circuit Breaker
- 8 - Control Power Disconnecting Device
- 9 - Reversing Device
- 10 - Unit Sequence Switch
- 12 - Overspeed Device
- 13 - Synchronous-speed Device
- 14 - Underspeed Device
- 15 - Speed - or Frequency-Matching Device
- 20 - Elect. operated valve (solenoid valve)
- 21 - Distance Relay
- 23 - Temperature Control Device
- 25 - Synchronizing or Synchronism-Check Device
- 26 - Apparatus Thermal Device
- 27 - Undervoltage Relay
- 29 - Isolating Contactor
- 30 - Annunciator Relay
- 32 - Directional Power Relay
- 36 - Polarity or Polarizing Voltage Devices
- 37 - Undercurrent or Underpower Relay
- 38 - Bearing Protective Device
- 39 - Mechanical Conduction Monitor
- 40 - Field Relay
- 41 - Field Circuit Breaker
- 42 - Running Circuit Breaker
- 43 - Manual Transfer or Selector Device
- 46 - Reverse-phase or Phase-Balance Relay
- 47 - Phase-Sequence Voltage Relay
- 48 - Incomplete-Sequence Relay
- 49 - Machine or Transformer Thermal Relay
- 50 - Instantaneous Overcurrent
- 51 - AC Time Overcurrent Relay

- 52 - AC Circuit Breaker
- 53 - Exciter or DC Generator Relay
- 54 - High-Speed DC Circuit Breaker
- 55 - Power Factor Relay
- 56 - Field Application Relay
- 59 - Overvoltage Relay
- 60 - Voltage or Current Balance Relay
- 61 - Machine Split Phase Current Balance
- 62 - Time-Delay Stopping or Opening Relay
- 63 - Pressure Switch
- 64 - Ground Detector Relay
- 65 - Governor
- 66 - Starts per Hour
- 67 - AC Directional Overcurrent Relay
- 68 - Blocking Relay
- 69 - Permissive Control Device
- 71 - Level Switch
- 72 - DC Circuit Breaker
- 74 - Alarm Relay
- 75 - Position Changing Mechanism
- 76 - DC Overcurrent Relay
- 78 - Phase-Angle Measuring or Out-of-Step Protective Relay
- 79 - AC-Reclosing Relay
- 81 - Frequency Relay
- 83 - Automatic Selective Control or Transfer Relay
- 84 - Operating Mechanism
- 85 - Carrier or Pilot-Wire Receiver Relay
- 86 - Lockout Relay
- 87 - Differential Protective Relay
- 89 - Line Switch
- 90 - Regulating Device
- 91 - Voltage Directional Relay
- 92 - Voltage and Power Directional Relay
- 94 - Tripping or Trip-Free Relay
- 95 - Reluctance Torque Synchrocheck
- 96 - Autoloading Relay

# Methods of Fault Detections

- Magnitude of current – Overcurrent protection
- Magnitude of current in earth and neutral – Earth fault protection
- Magnitude and angle of Impedance (Ratio V/I) Impedance protection
- Difference between two currents – Differential protection
- Difference between phase angles of two currents – phase comparison protection
- Magnitude of negative sequence current
- Magnitude of voltage – Overvoltage or undervoltage protection
- Magnitude of frequency – Overvoltage or underfrequency protection
- Temperature – Thermal protection
- Specials i.e. transformer gas protection




# Zones of Protection

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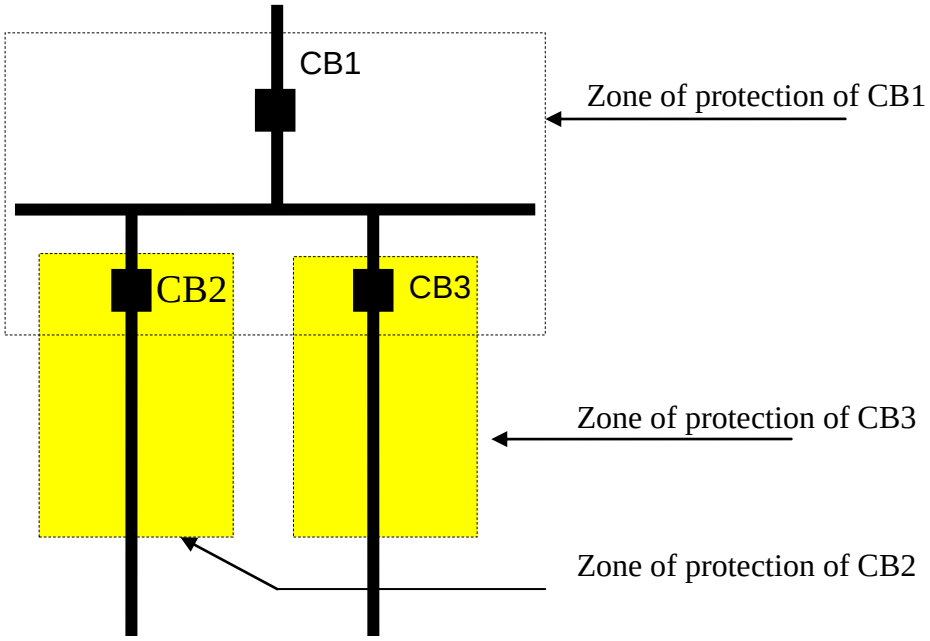
|---|---|
| Zones of Protection | |

# Zones of protection

Zone of protection of a relay is the place or the distance that the relay can protect easily.Fig.1 shows an example of protection zones for three circuit breakers.It is to be noted that the protection zones are overlapped.




In power systems, all power system elements must be encompassed by at least one zone

- The more important elements must be included in at least two zones
- Zones must overlap to prevent any element from being unprotected.
- The overlap must be finite but small to minimize the likelihood of a fault inside this region.
- A zone boundary is usually defined by a CT and a CB.
- *The CT provides the ability to detect a fault inside the zone*
- *The CBs provide the ability to isolate the fault.*

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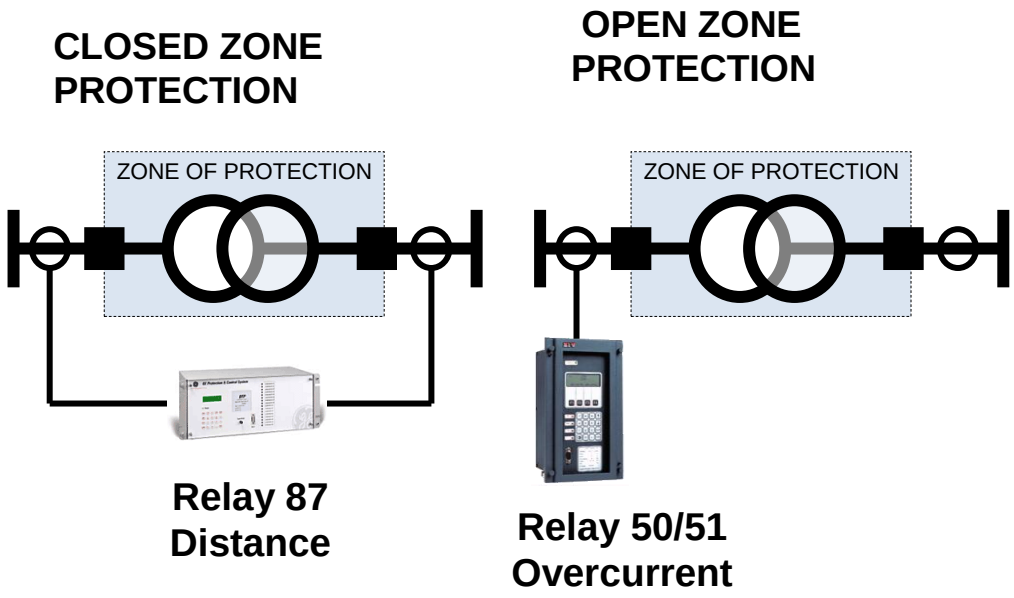
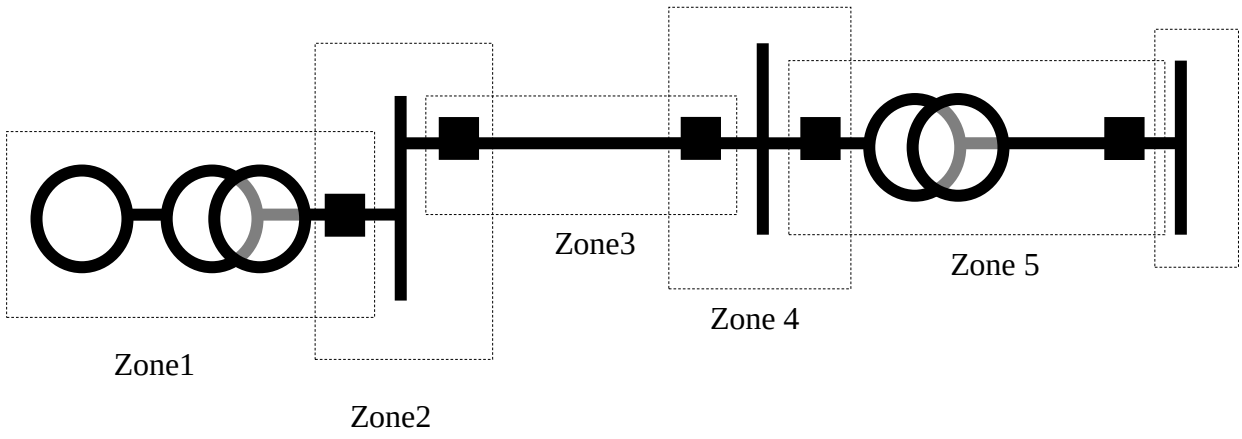
| Zones of Protection | |

## *CLOSED AND OPEN PROTECTION ZONES*




## Primary Zones of protection



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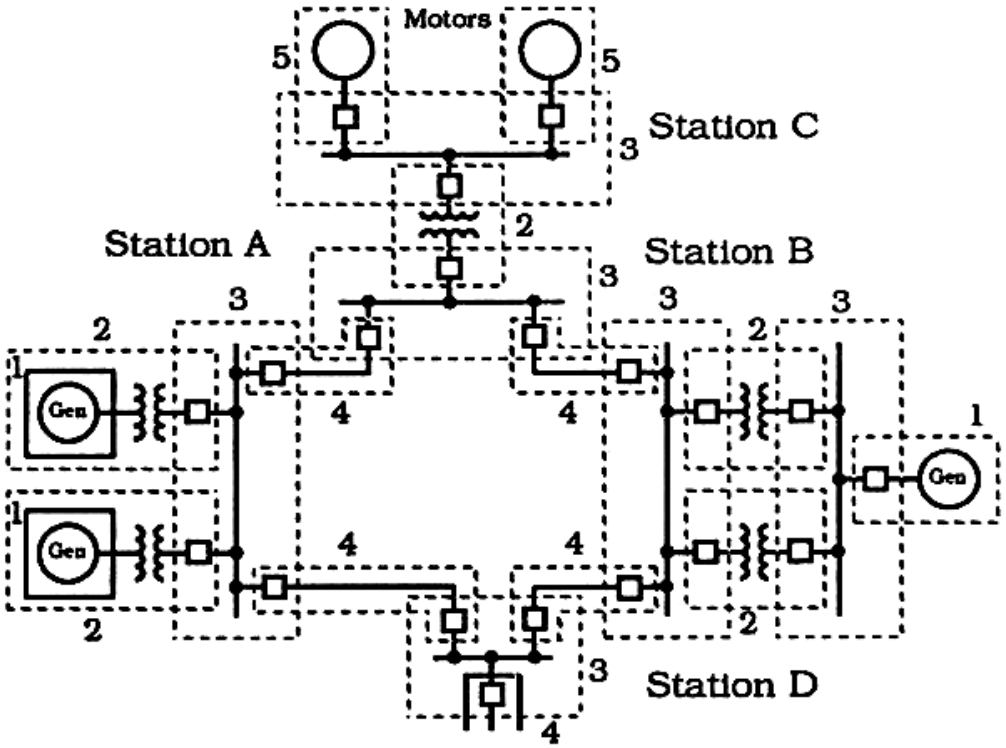
|---|---|
| Zones of Protection | |

# Primary protection in power systems




Primary protection zones for a typical power system

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| Zones of Protection | |

# Backup protection

- It is essential that provision be made to clear the fault by some alternative protection system in case of the primary protection fails to operate. These are referred to as backup protection systems

- Ideally primary and backup are independent (relay,breaker,CT,PT)

- Slower than primary

- Sometimes backup protection opens more circuit breakers than absolutely necessary to clear the fault

- Provide primary protection when usual primary equipment out of service

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|---|---|
| Zones of Protection | |

# Two Types of Backup Protection

Back up relaying may be installed locally, in the same substation, or remote in other substations or places:

- Local backup : Clears fault in the same station where the failure has occurred
- Remote backup : Clears fault on station away from where the failure has occurred

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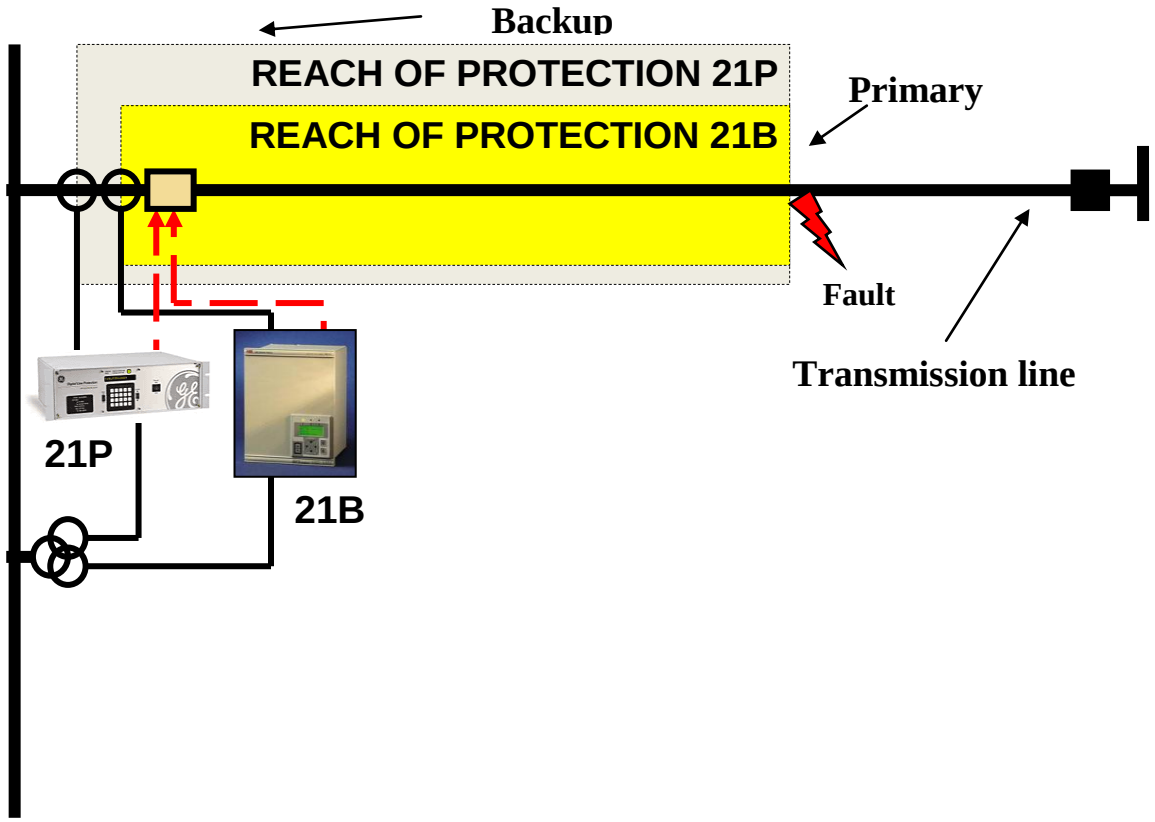
| Zones of Protection | |

# Primary and Back up protection at the same location ( Local Backup)



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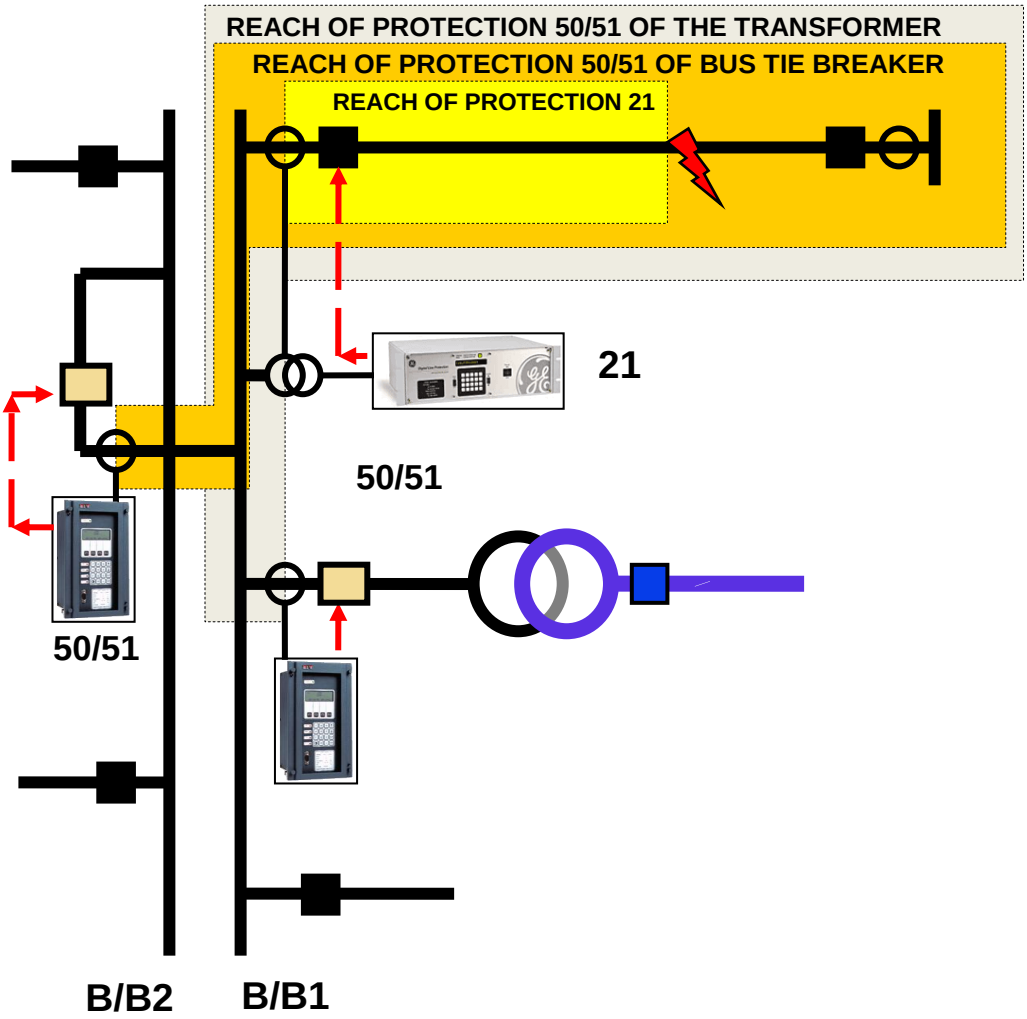
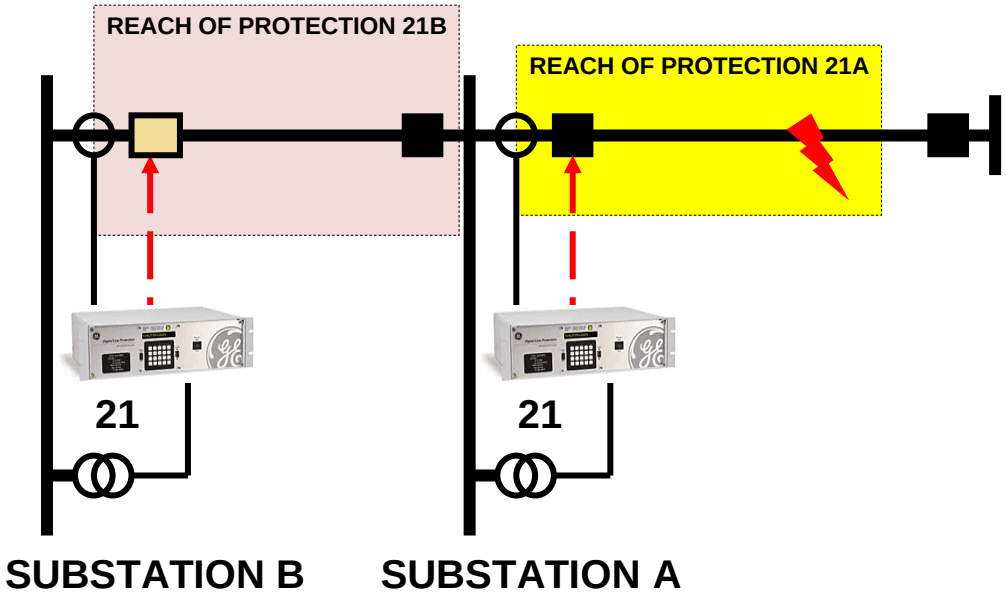
|---|---|
| Zones of Protection | |

# Local backup protection at differente locations



| Power System protection | Dr. Mohamad Tawfeeq |
|---|---|
| Zones of Protection | |

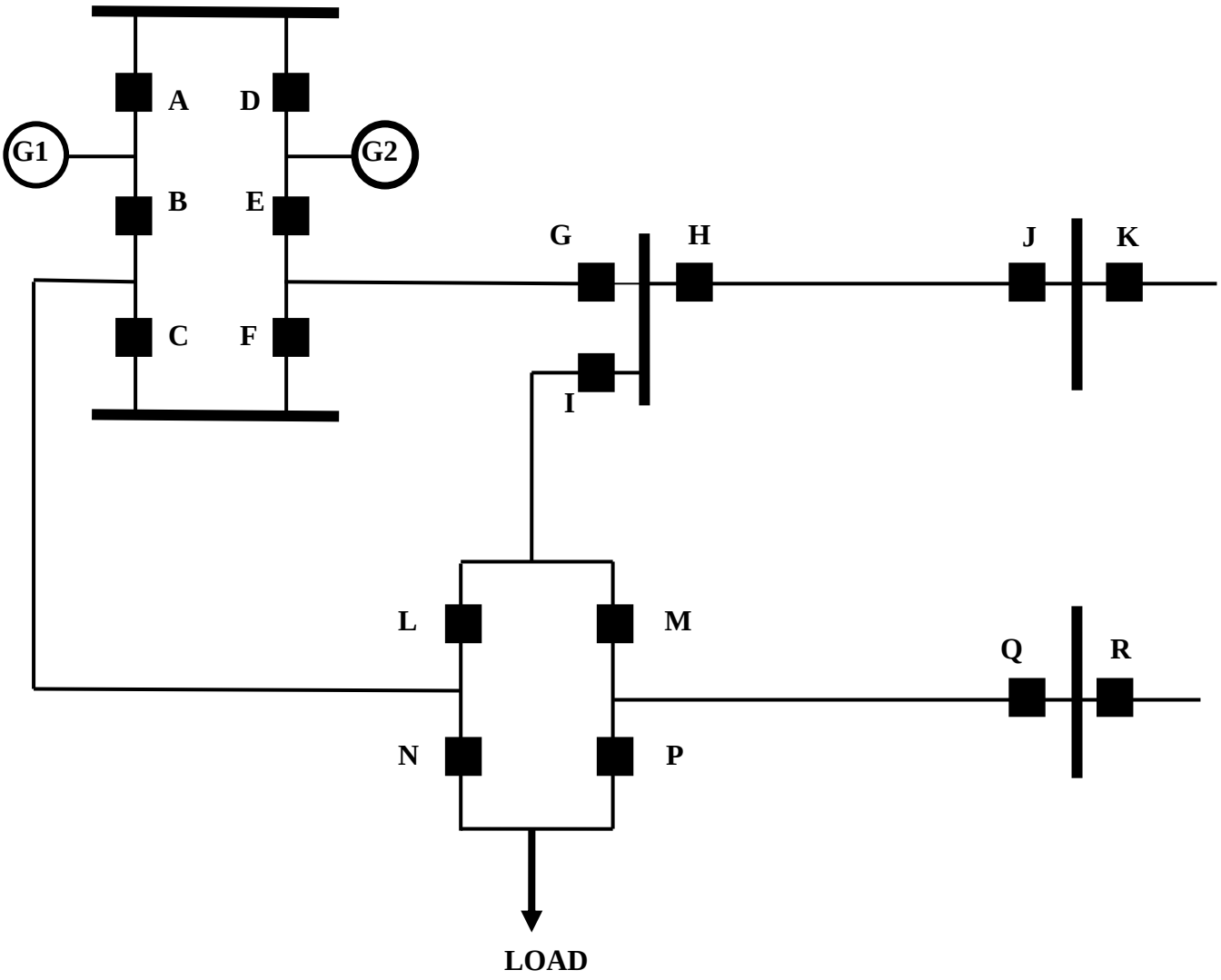
# Remote back up protection




- **Selectivity and zones of protection**
  Selectivity is defined in terms of regions of a power system (zones of protection) for which a given relay is responsible.

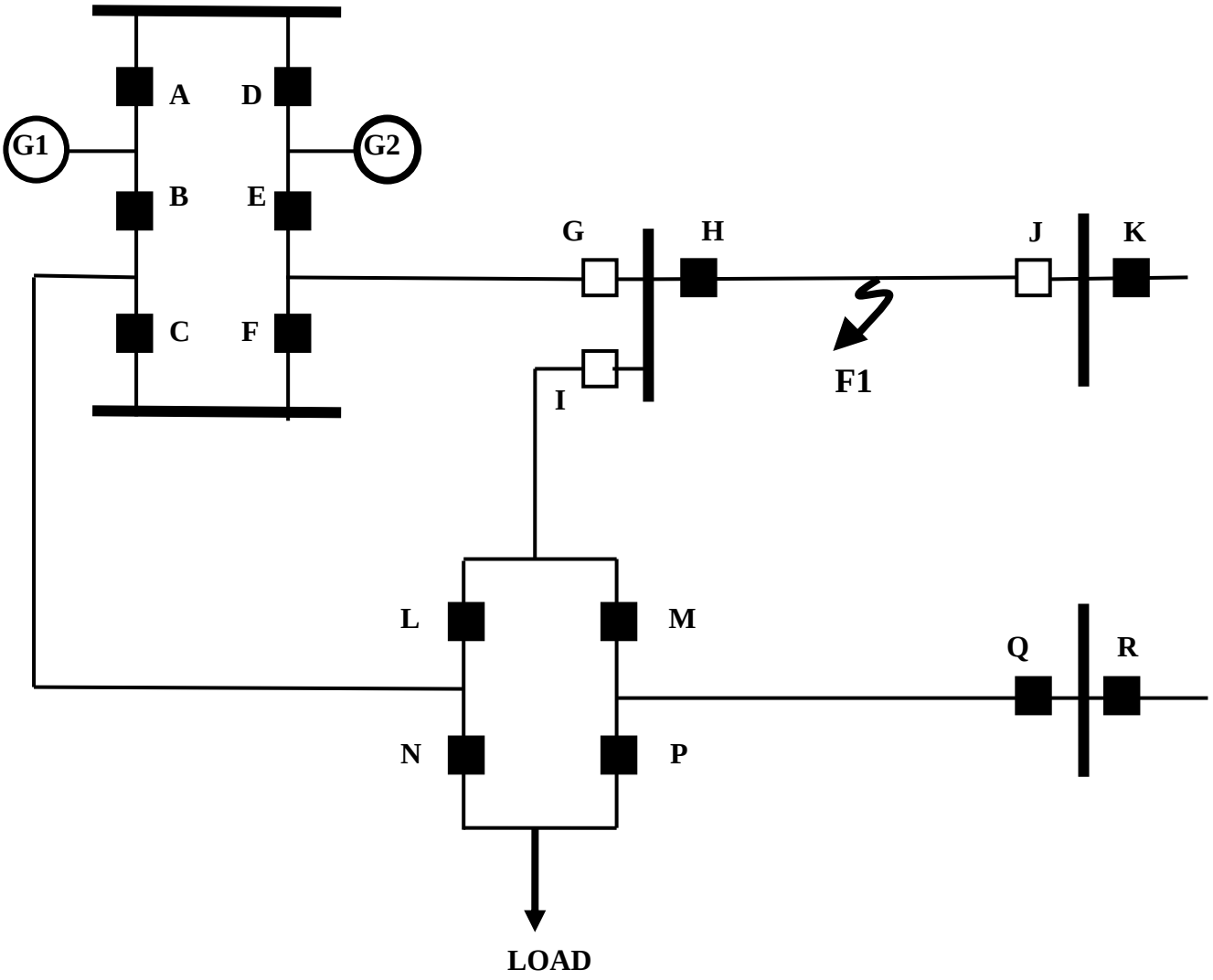
- The relay will be considered **secure** if it responds only to faults within its zone of protection

**Example : Consider the following simple power system:**




Discuss the local and remote backup protection for two fault locations as follows:

# Case 1: Local Backup



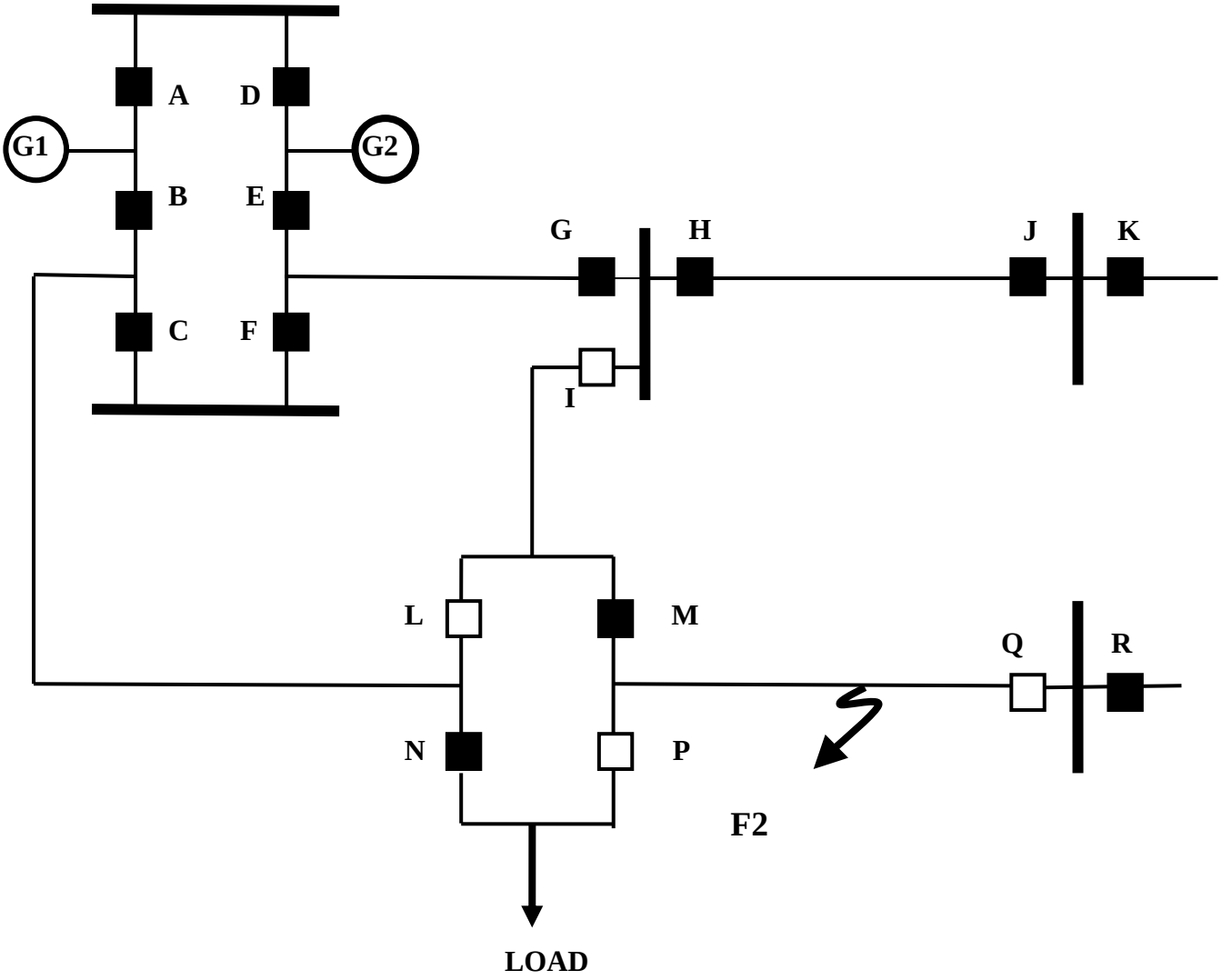

■ **Breaker closed** □ **Breaker opened**

For fault at F1: Suppose that breaker **J** operate and breaker **H** failed to operate.

Therefore:

**G** and **I** must operate as **<u>local backup</u>** protection

# Case 2: Local Backup

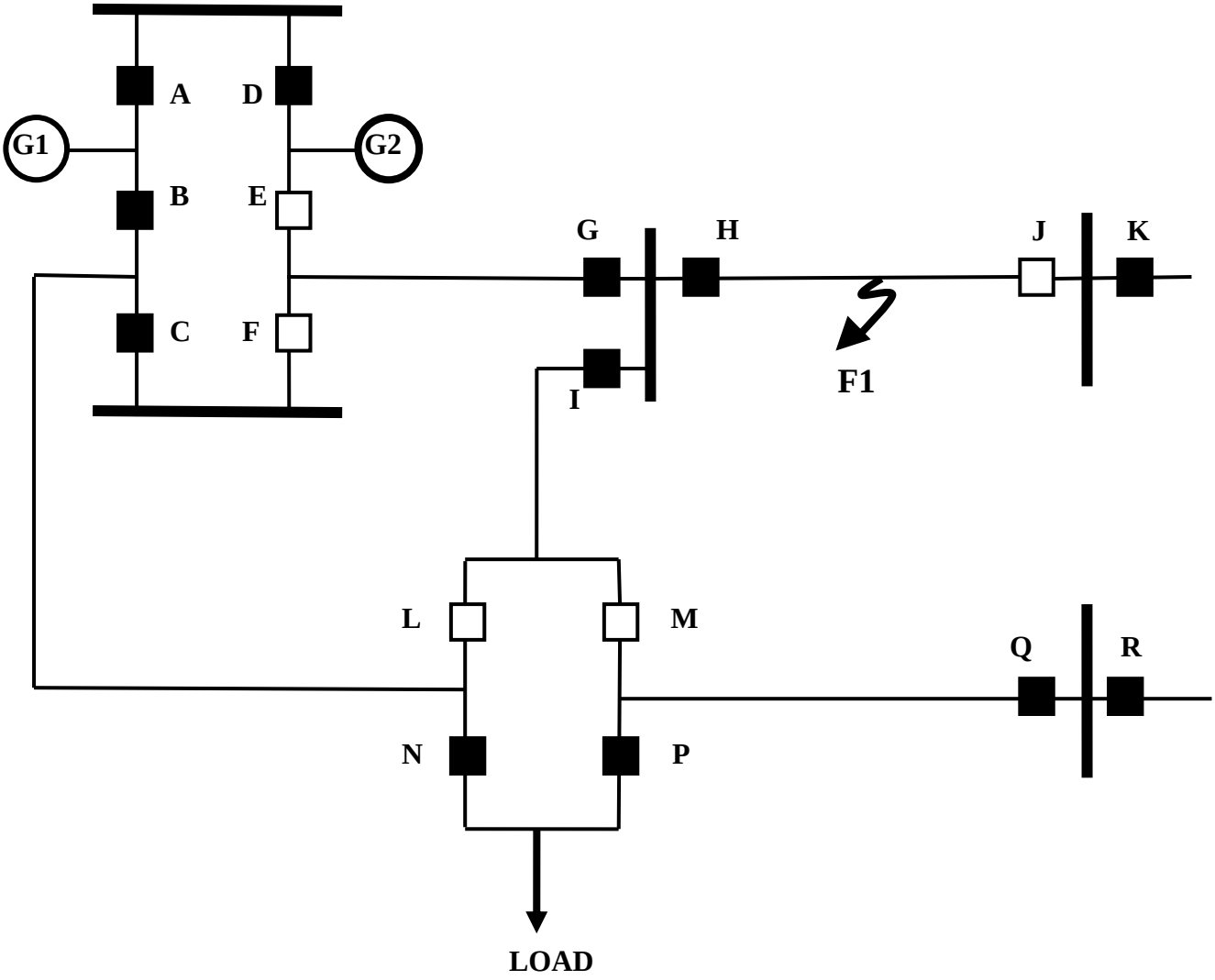



■ **Breaker closed** □ **Breaker opened**

For fault at F2: Suppose that breakers P and **Q** operate and breaker **M** failed to operate.
Therefore:

**L** must operate as **<u>local backup</u>** protection and **I should tripped by communication signal (Transfer Trip)**

# Case 3: Remote Backup

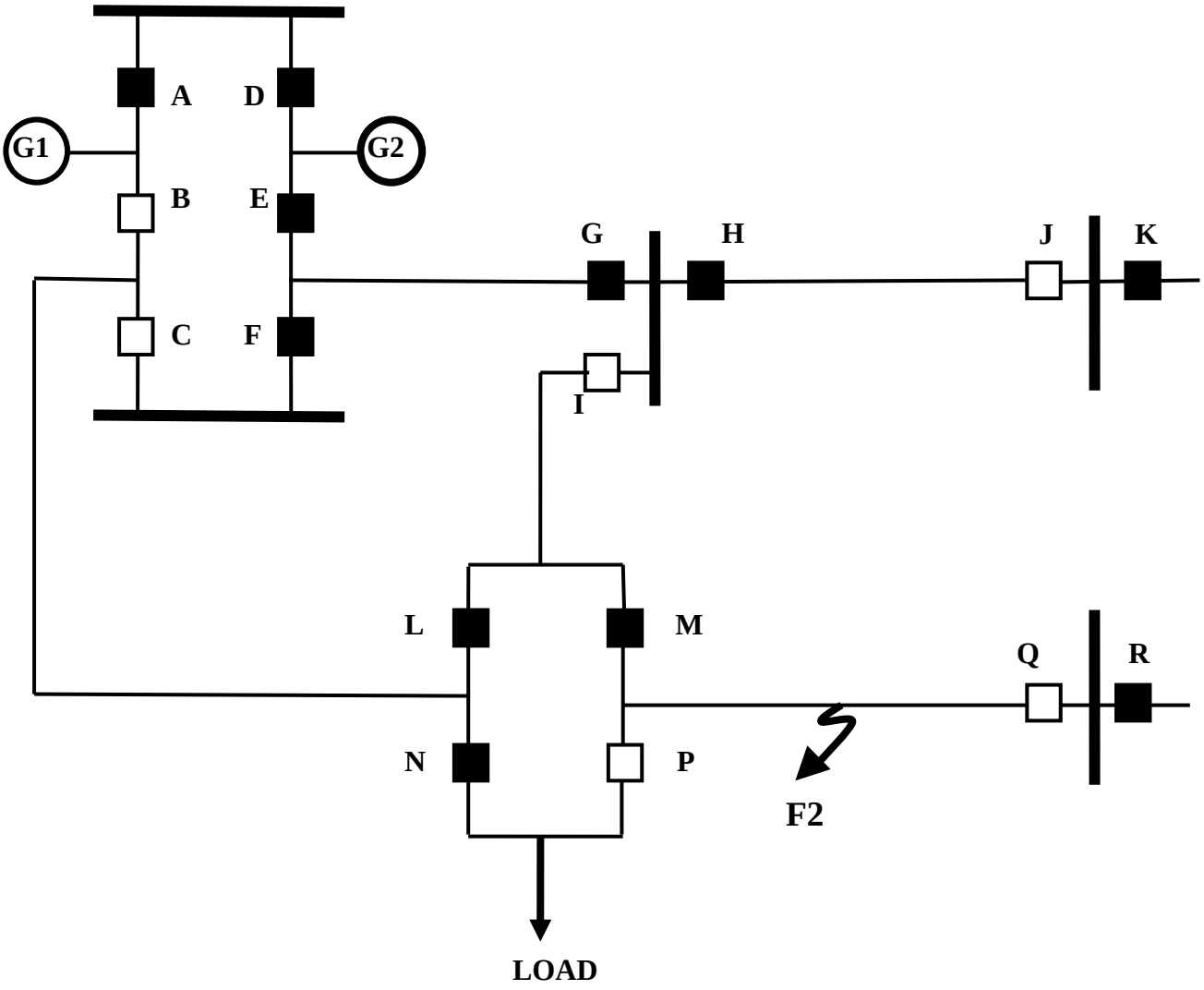



■ **Breaker closed** □ **Breaker opened**

For fault at F1: Suppose that breaker **J** operate and breaker **H** failed to operate.
Therefore:

**E, F, L** and **M** must operate as **<u>Remot backup</u>** protection

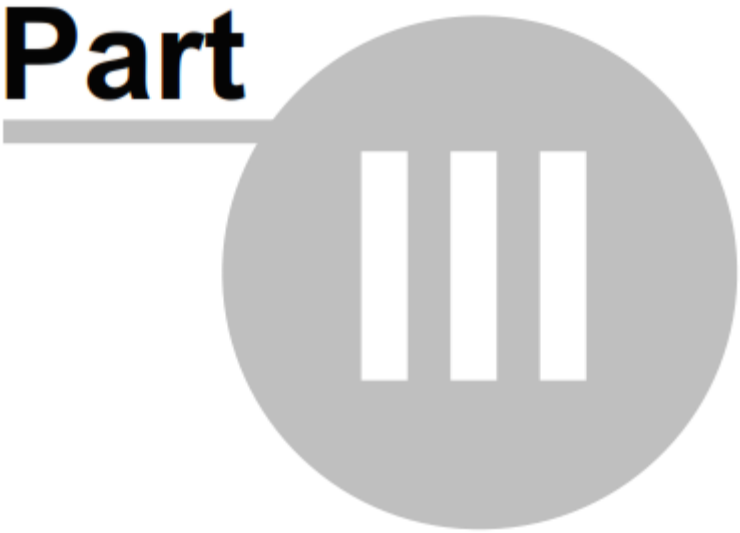
# Case 4: Remote Backup




■ **Breaker closed** □ **Breaker opened**

For fault at F1: Suppose that breakers **P & Q** operate and breaker **M** failed to operate.
Therefore:

**I, B,** and **C** must operate as **<u>Remot backup</u>** protection




# Instrument Transformers

| **Power System protection** | **Dr. Mohamad Tawfeeq** |
|---|---|
| **Instrument Transformers** | |

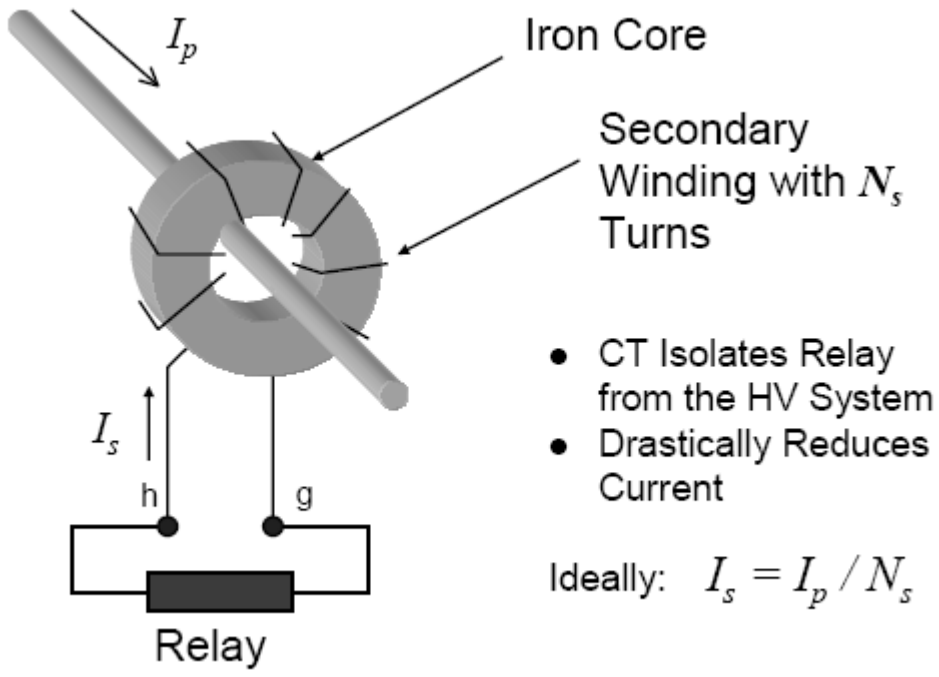
# Instrument Transformers

- CT – Current Transformer
- Current Scaling
- Isolation
- VT – Voltage Transformer
- Voltage Scaling
- Isolation

## 1.Current Transformers

- Current and voltage transformers are responsible for scaling primary system signals.
- Typical nominal secondary values are 5 A and 1 A for current transformers and 110 V for voltage transformers.
- Conventional magnetic current and voltage transformers are still in wide use in power systems. For voltage levels greater than 230 kV, we substitute capacitive-coupled voltage transformers (CCVT) for VTs.CT saturation and bad transient response of CCVTs create protection problems.
- New trends in current and voltage transducers are low-power-output current and voltage transformers (recently included in an IEC Standard) and magneto-optic current and voltage transducers (MOCT and MOVT). MOCTs use the Faraday Effect, and MOVTs can use either the Faraday or the Pockels effect.

# Principles of Current Transformers




The initial problem was how to connect a low-voltage device to the high-voltage system and have the ability to handle large fault currents (kilo-Amps). How can we make the relay measure the currents flowing in the high-voltage system in order to detect these faults?

The solution consists of using a special type of transformer, called a current transformer.

The main parts of a current transformer are:

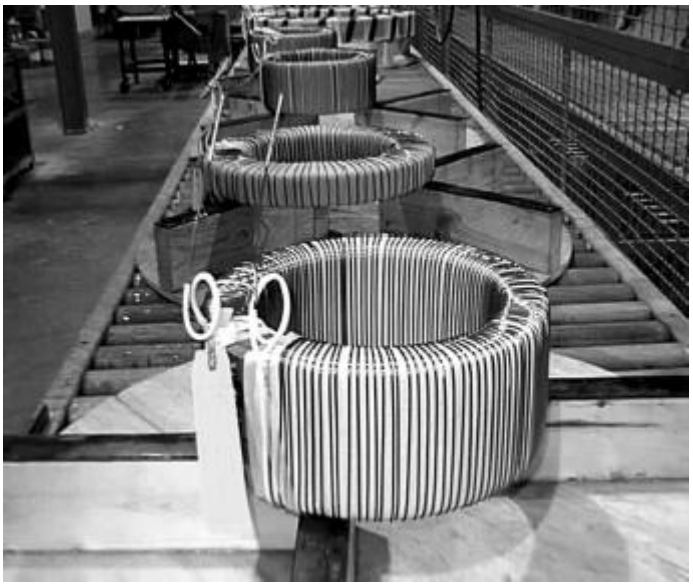
• Iron core
• Secondary winding
• Primary conductor
• External insulation

Some current transformers do not have a primary conductor. In those cases the primary is the line or bus itself. Sometimes the core and its secondary winding are directly installed in the bushing of the circuit breakers or transformers. These CTs are called “bushing CTs”.

Some current transformers may have a primary that consists of several turns. Typically there are no more turns than the natural, which is equivalent to say that the primary number of turns is 1.

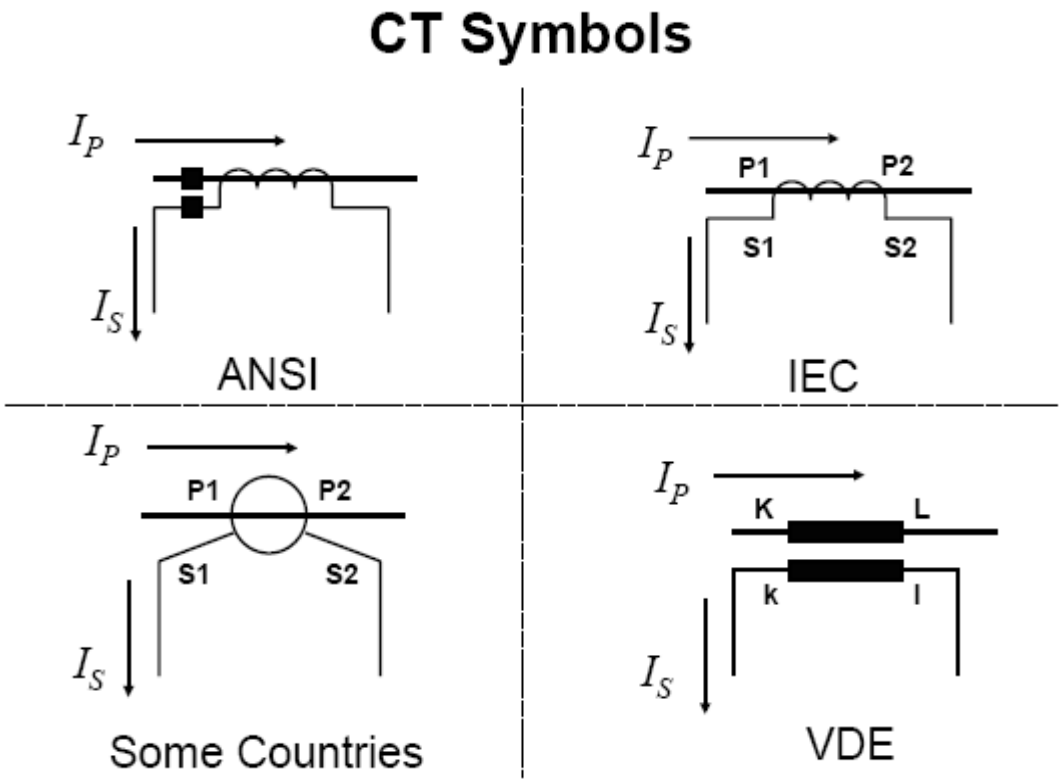
The total load connected to the CT terminal (g and h in this case) is called “burden”.

Ideally, the secondary current of a CT is perfectly proportional to the primary current. It will be shown later that in reality this is sometimes not true.



## Core and Secondary Winding Example

## High-Voltage CT Example



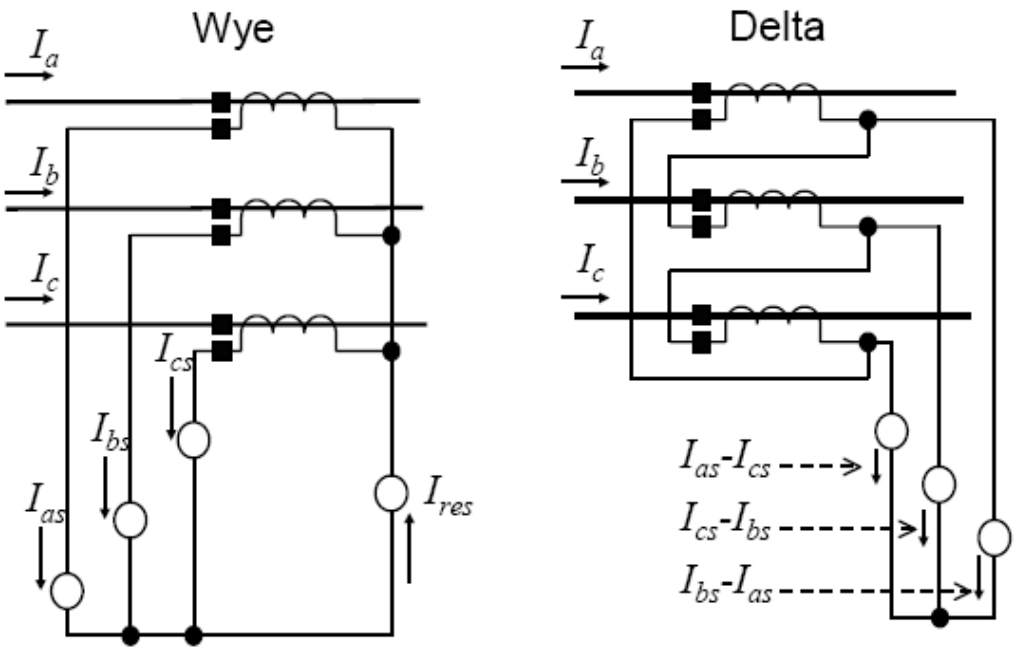

Note that in all cases there are polarity marks. The following conventions are used to mark the reference for AC currents:

ANSI: Polarity marks

IEC: P1, P2, S1, S2

VDE: K, L, k, l

# CT Common Connections




These are the two of the most common connections of current transformers in three phase systems.

At the left, the “Y” connection provides the line currents at the secondary.
At the right, the “Δ” connection provides the difference currents (delta currents) to the secondary loads.

## Current Transformer Ratio (CTR)

The Current Transformer Ratio, CTR, expressed as a fraction, is the ratio between the magnitudes of the primary and the secondary current for ideal working conditions of the current transformer.

$$CTR = \frac{I_P}{I_S}$$

Examples: CTR = 200/5 = 40
CTR = 1200/5 = 240
CTR = 400/1 = 400

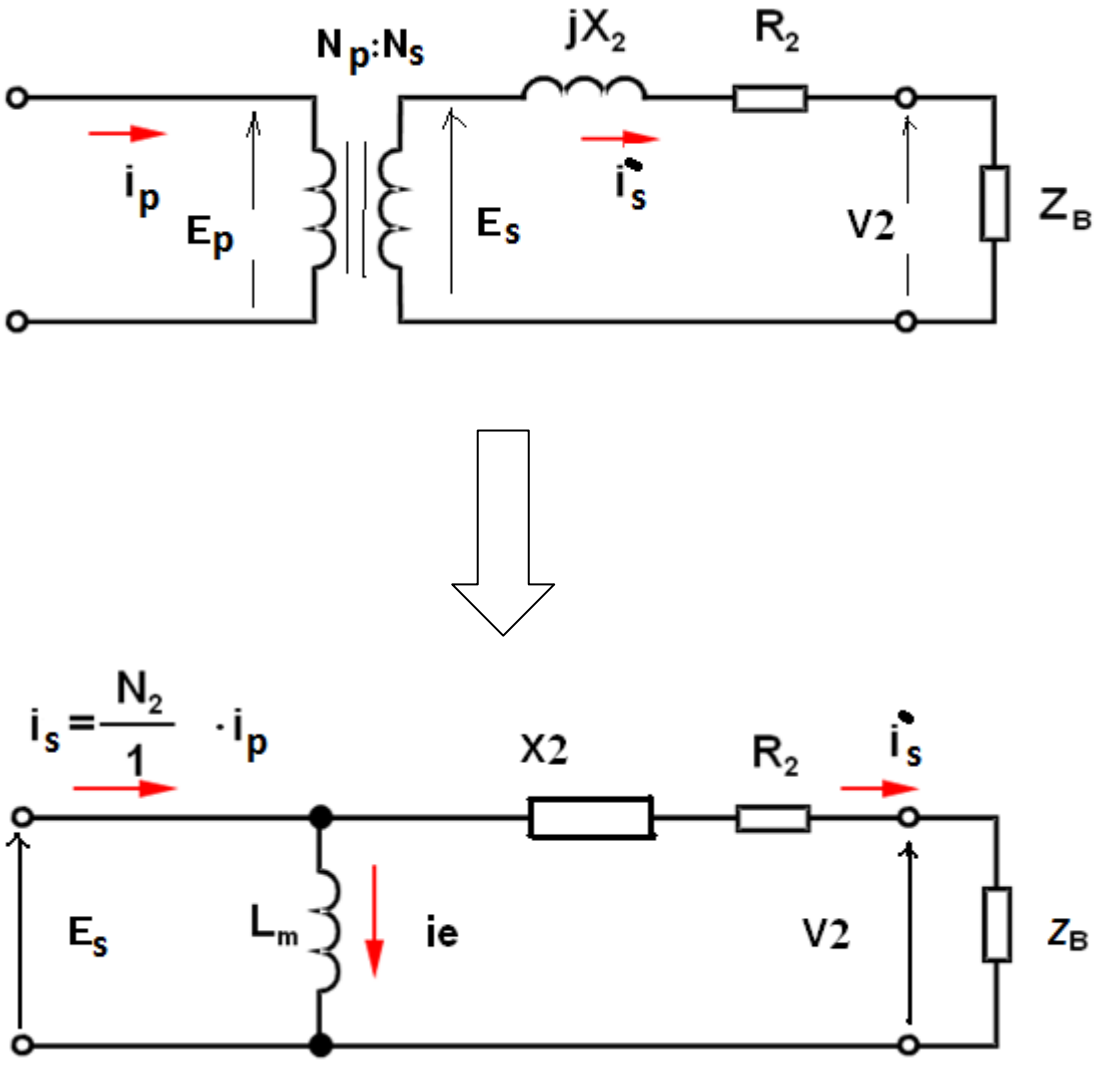
- Denominator is the Secondary Rated Current
- Typically: 1 A or 5 A
- Numerator Is Not Always the Primary Rated Current

### IEC Standard Accuracy Classes

- The IEC (International Electrotechnical Commission) Specifies Current Transformers as:

15 VA Class 10 P 20
- 15 VA: Continuous VA
- 10: Accuracy Class
- P: For Protection
- 20: Accuracy Limit Current Factor

# Current Transformer Equivalent Circuit



# CT Performance Calculations

The performance of a C.T may be found from two approaches :

1. The formula method.
2. The saturation curve method.

**1- Formula Method .**

**Core Parameters**

**Es = 4.44 * Ns * f * Øm**

**Es = 4.44 * Ns * f * Bm *A**

Es = Voltage (v)

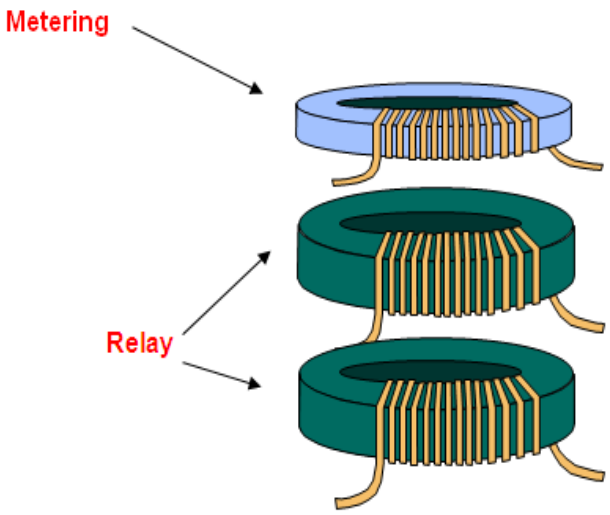
Bm = Maximum Flux density (Tesla)

F = Frequency (Hz)

A = Core area ($m^2$)

Ns = Number of secondary turns

Øm =Maximum Flux (Web)




**2- The saturation curve and error method**.

The relation between $E_s$ and $I_e$ is not linear like the relation shown in the Fig.1 due to the saturation of C.T core. Therefore the C.T. has ratio error.

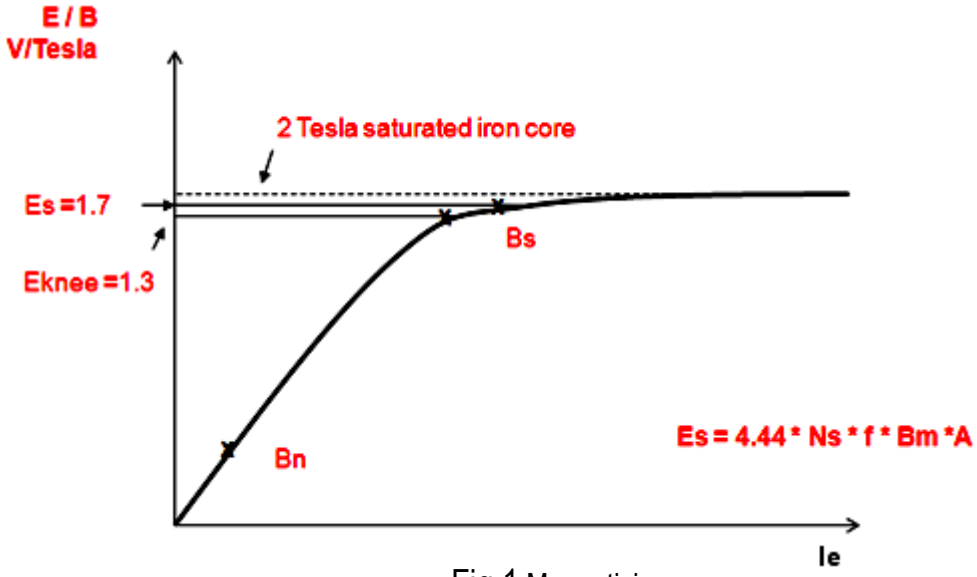



Fig.1 Magnetizing curve

- The deviation of $I_s$' from $I_s$ is called the C.T error, and can be expressed as a percentage.

$$C.T_{error} = \frac{I_s - I_s^{'}}{I_s} x100\% = \frac{I_e}{I_s} x100\%$$

**Where:**

$I_s - I_s^{'} = I_e$

$I_s$: Total current in the CT secondary
$I_s^{'}$: Current due to the CT load

## Example:

Assume that a C.T has rated current ratio of 500/5 A. The impedance of the secondary winding $Z_2 = 0.242\ \Omega$, and the burden impedance $Z_B = 0.351\ \Omega$ .The core area A = 0.00193 $m^2$. The C.T must operate at máximum primary current of 10 kA.If the frequency is 60 Hz and the core is built from silicon steel:

(a) Determine whether or not the C.T will saturate.
(b) Determine the C.T error.

Solution

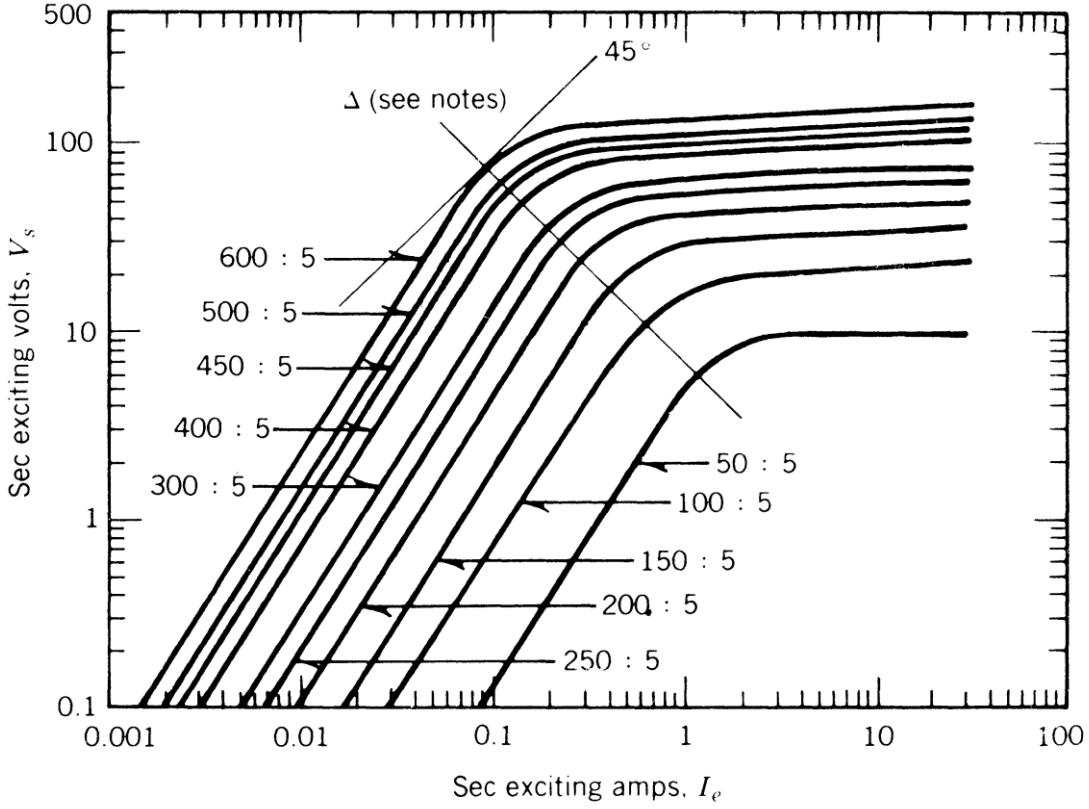
$I_s$= 10,000 x (5/500)= 100 A
If we neglect the excitation current Ie.
$I_s^{'} \approx I_s$= 100 A.
$E_s = I_s (Z_B+Z_2)$
= 100 x (0.351 +0.242) = 59.29 V
$E_s = 4.44 * f * N_2 * A * B_m$
**So:**

$$B_m = \frac{59.29}{4.44x60x\frac{500}{5}x0.001935} = 1.15T$$

As we know that the lower limit for the silcion steel saturation is $B_m$ = 1.2T Hence the C.T will not saturate.
From the saturation curve the core corrsponding Ie for $E_s$ = 59.29 V is $I_e$ = 0.1 A.

$$\text{C.T}_{\text{error}}\ \% = \frac{I_e^{'}}{I_s} x100\% = \frac{0.1}{100} x100\% = 0.1\%$$

## Saturation Curve for Silicon Steel Used in Current Transformer Cores for different CTRs.



# CT Classes and accuracies

## Accuracy Class

| Class | % error | Applications |
|---|---|---|
| **0.1** | **± 0.1** | **Metering** |
| **0.2** | **± 0.2** | |
| **0.5** | **± 0.5** | |
| **1.0** | **± 1.0** | |
| **5P** | **± 1** | **Protection** |
| **10P** | **± 3** | |

C.T specifications:

- A rated burden at rated current or (VA).
- An accuracy clases
- (ALF) accuracy limit factor an upper limit beyond which the accuracy is not guaranteed.

Example:

1. 15 VA clases 0.5→mettering C.T
2. 15 5p 20 →protection C.T

Rated burden 15VA
Accuracy class 5p
ALF= 20 (20 times the rated current)

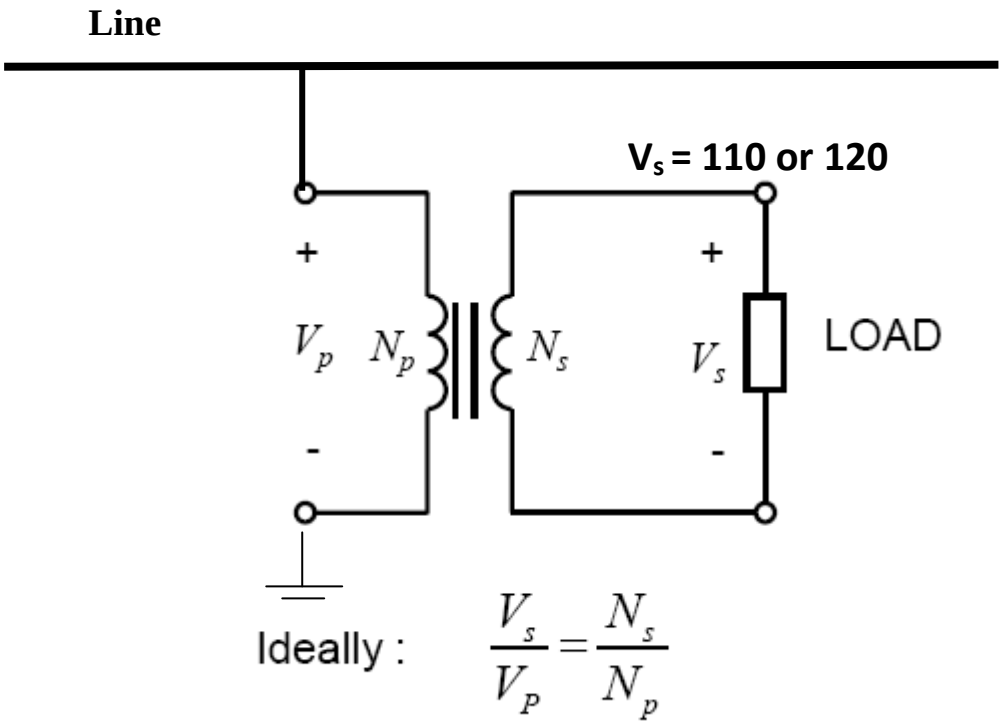
| Power System protection | Dr. Mohamad Tawfeeq |
|---|---|
| Instrument Transformers | |

# 2.Voltage Transformers

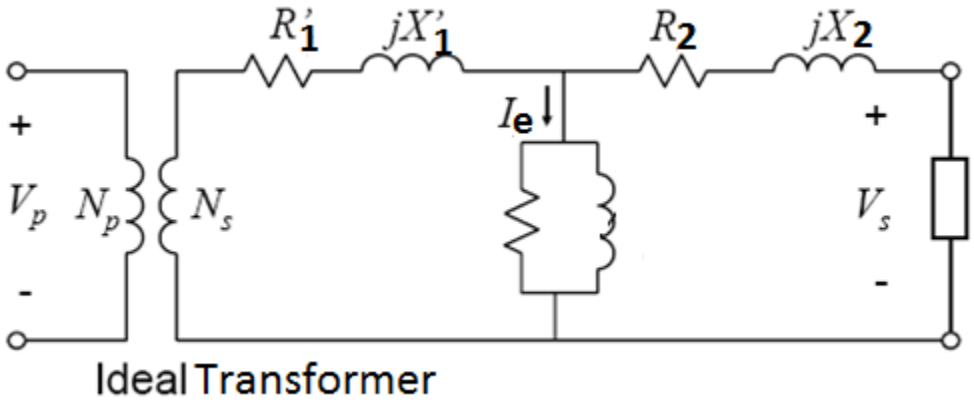
Voltage transformers are connected across the points at which the voltage to be measured.
Types of voltage Transformers:
There are three main types of voltage transformers:

- Magnetic voltage transformers (ordinary two winding type – used for L.V. and M.V).
- Capacitive Voltage Transformers (CVT), used for high and extra high voltages.
- Magneto—optic voltage transformers (new ).

## 2.1 Magnetic Voltage Transformer (VT)



# VT Equivalent Circuit
## Referred to the Secondary Side




# 2.2 Capacitive Voltage Transformers (CVT)

**There are two types of CVTs:**

- **Coupling capacitor voltage transformer**
- **Capacitor – bushing voltage transformer**

**These types are shown in figure below:**

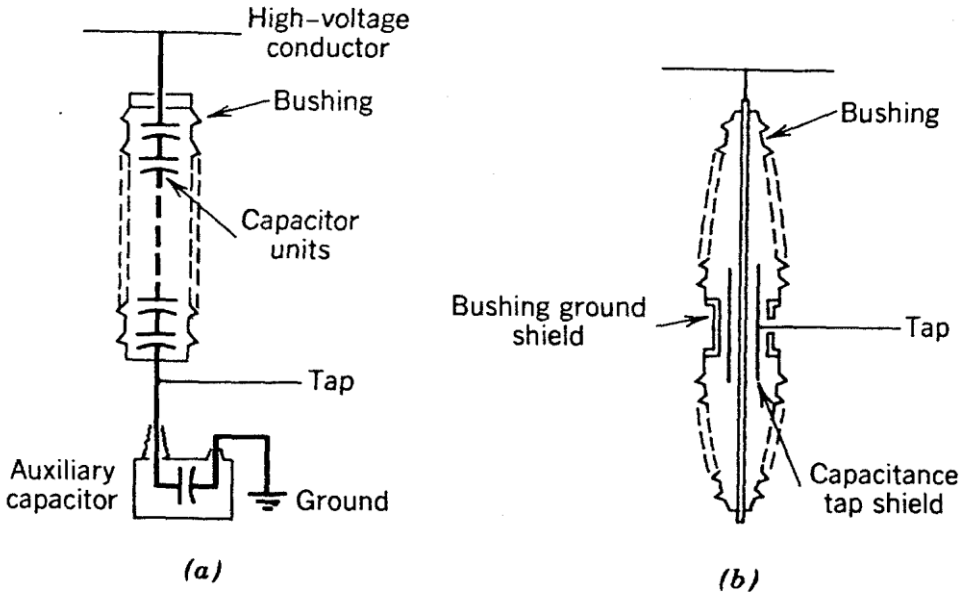
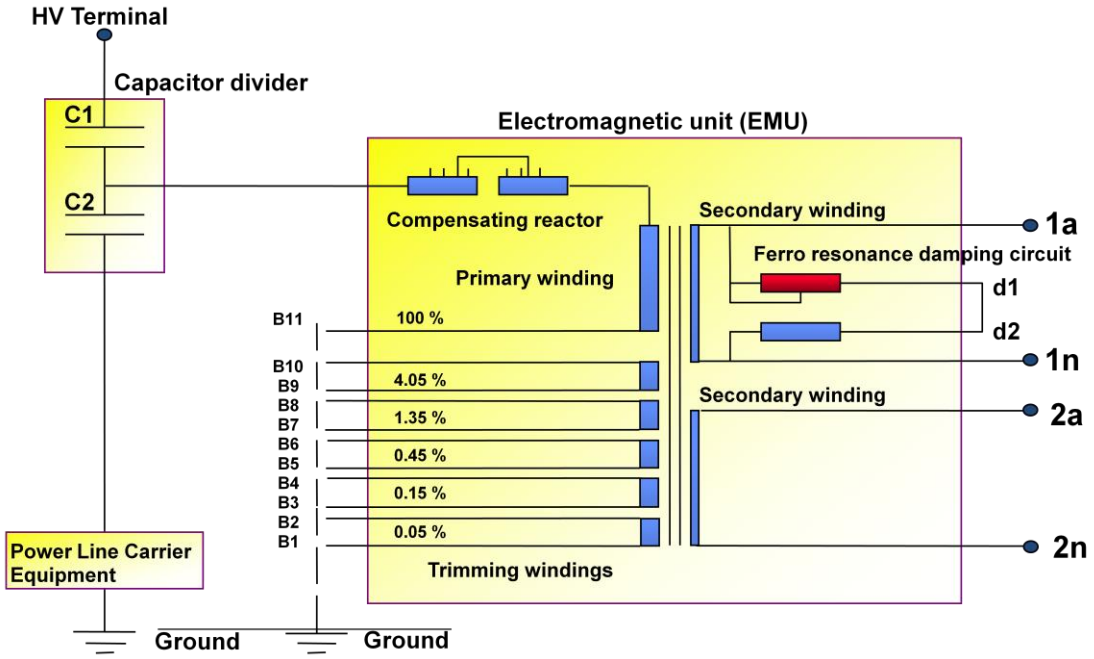
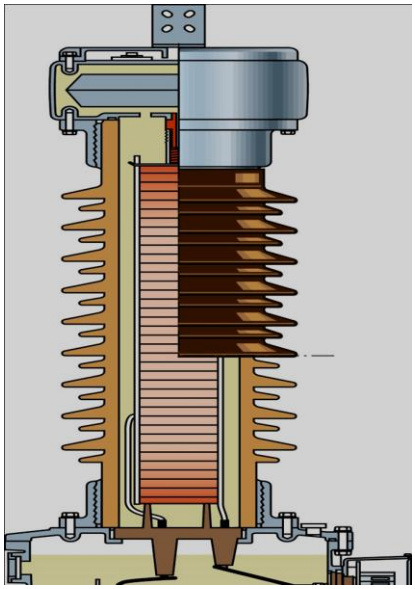
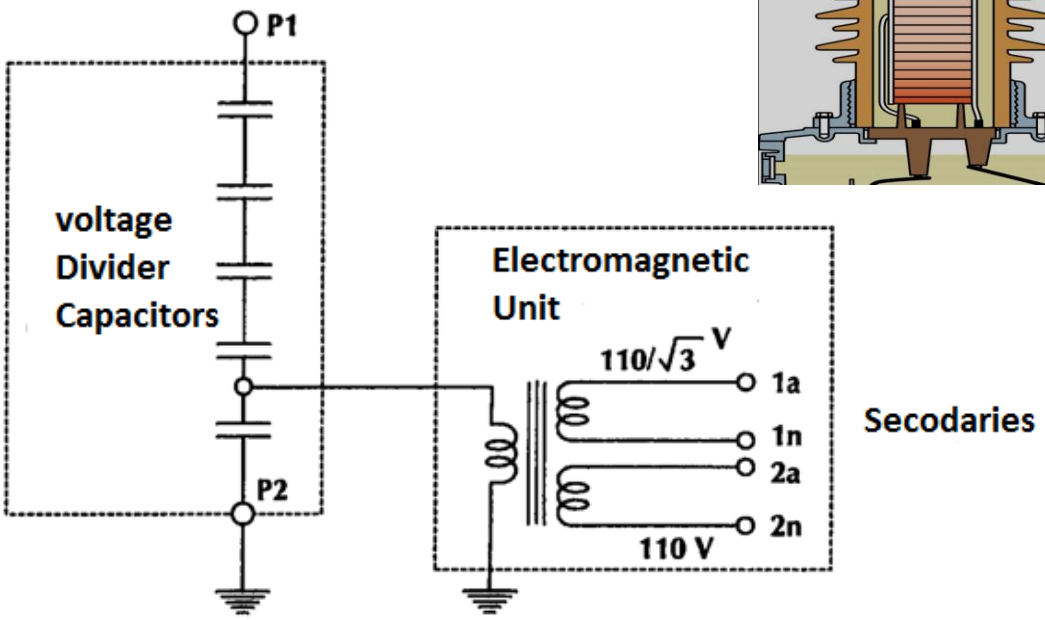


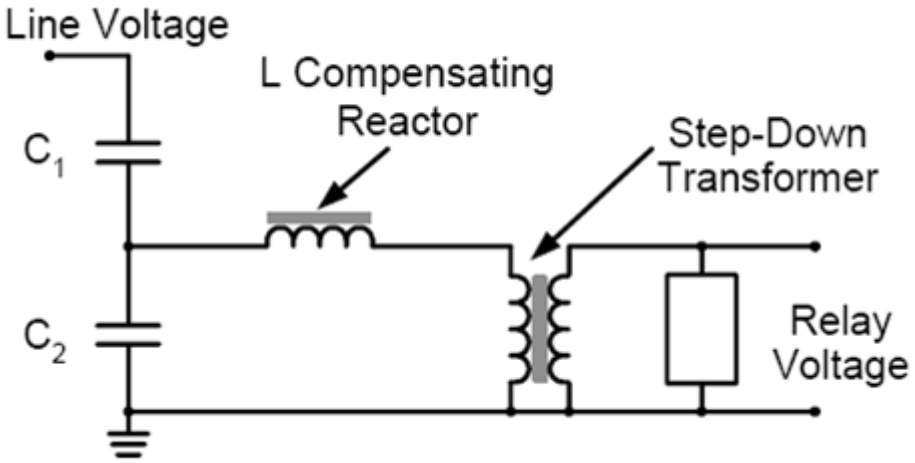

Figure : Capacitor voltage transformers: (a) coupling-capacitor voltage divider (b) capacitance-bushing voltage divider .




# CVT equivalent circuit








VT error : Errors in magnitude can be calculated from :

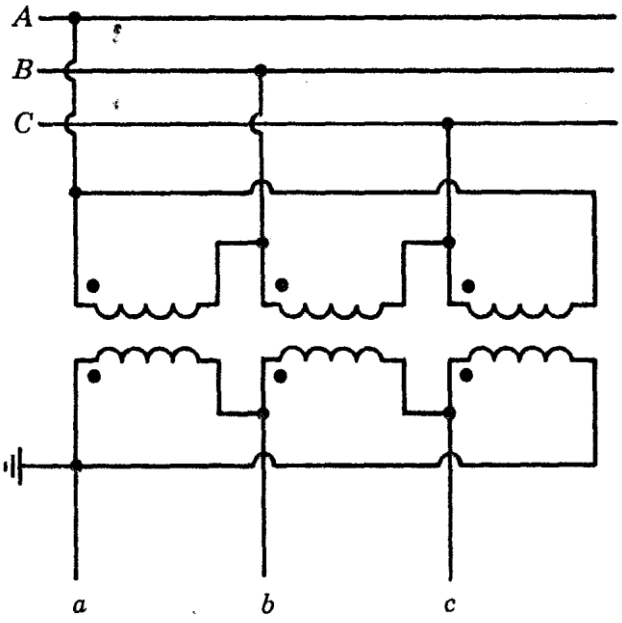
$$Error_{VT} = \{(n V_s - V_p) / V_p\} \times 100\%.$$

**Table : Voltage transformers error limits**

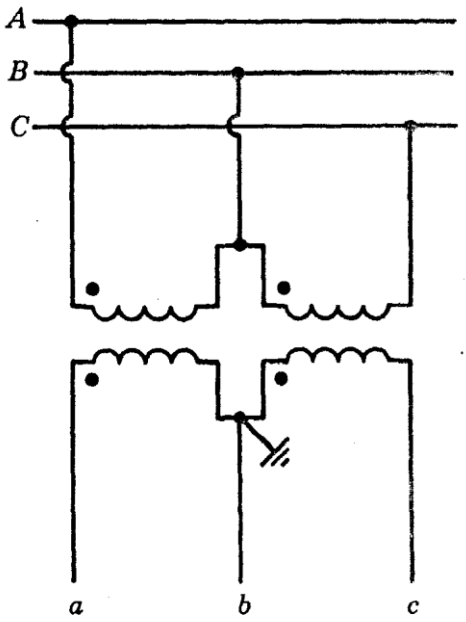
| Class | Primary voltage | Voltage error (±%) | Phase error (±min) |
|---|---|---|---|
| 0.1 | **0.8 $V_n$ , 1.0 $V_n$ and 1.2 $V_n$** | 0.1 | 0.5 |
| 0.2 | | 0.2 | 10.0 |
| 0.5 | | 0.5 | 20.0 |
| 1.0 | | 1.0 | 40.0 |
| | | | |
| 0.1 | **0.5 $V_n$** | 1.0 | 40.0 |
| 0.2 | | 1.0 | 40.0 |
| 0.5 | | 1.0 | 40.0 |
| 1.0 | | 2.0 | 80.0 |
| | | | |
| 0.1 | **$V_n$** | 0.2 | 80.0 |
| 0.2 | | 2.0 | 80.0 |
| 0.5 | | 2.0 | 80.0 |
| 1.0 | | 3.0 | 120.0 |

**$V_n$ =Nominal voltage**

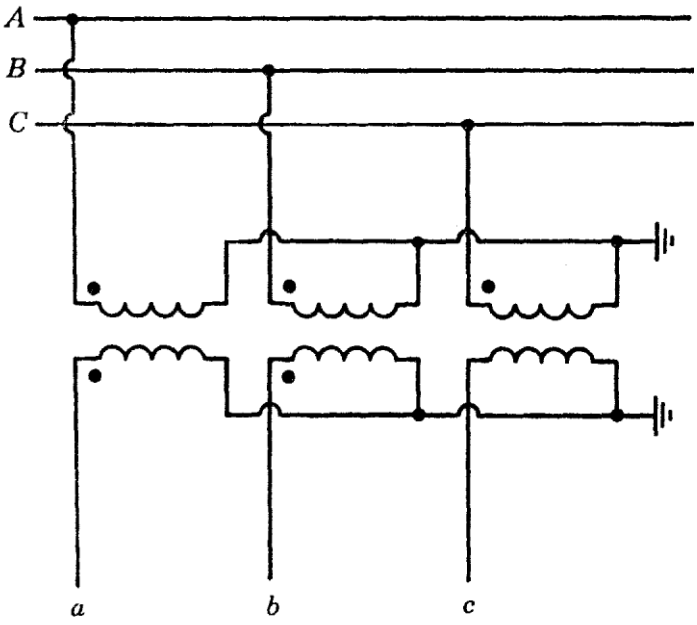
# VT connections




**(b) delta – wye connection**




**(a) Open delta connection**




(c) **wye—wye connection**

# Power system Protection

# Protective Devices:
# Fuses & Circuit Breakers

**Dr.Professor Mohammed Tawfeeq Lazim Alzuhairi**

**Power system protection Dr.Prof. Mohammed Tawfeeq**
**Protective Devices: Fuses & Circuit Breakers**

## FUSES

### *1. Low voltage* fuses

The fuse is the oldest device used to protect electrical circuits and equipments against overload and short circuits.
The fuse can have many forms and shapes depending on its application. Its rating can start from few mA to several kA.
Type of Fuses:
Depending on the fuse current rating, the fuses can be one of the following types for low voltage applications:
1- Semi - enclosed Fuse (Rewirable)
2- Cartridge Fuse.
3- High Rupturing Capacity (H.R.C) or High Breaking Capacity (H.B.C) Fuses.

***The Semi-enclosed Fuse:***
This type is made from two sections, the base and the carrier. Both of them are made from porcelain insulator. The fuse is so designed that the carrier can be safely withdrawn without danger of touching live parts and the fuse element is so enclosed that molten metal is safely contained and arcing effectively extinguished.
The simple wire fuse (Fig.1) is connected between two terminals in a porcelain carrier and is usually threaded through an asbestos tube.

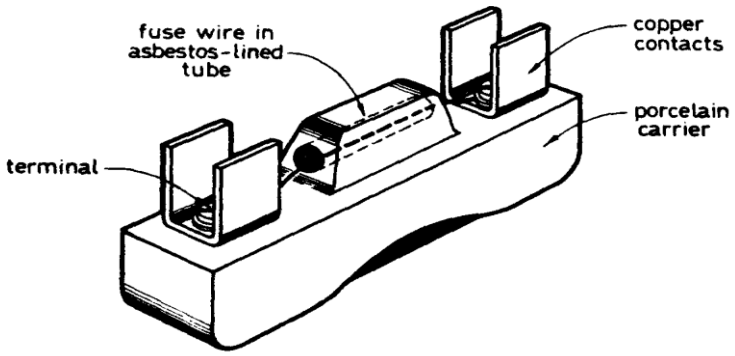



**Fig.1 Semi - enclosed (rewirable) Fuse** .

The fusing current for this type of fuse may vary considerably. Circulating air can cool the wire, thereby increasing the fusing current. Air will also oxidize the wire in time, and this will cause a reduction of the fusing current. If discrimination is required, or accuracy in the value of the fusing current is necessary, then the wire fuse is most unreliable. The wires deteriorate and are subject to misuse, since it is easy for the wrong size of wire to be fitted. In circuits where the energy level is high, the wire fuse can be a source of danger, as it may not be adequate in extinguishing the arc.

## *The Cartridge Fuse:*

Some of the disadvantages of the Semi - enclosed fuse are overcome if the wire is enclosed in a cartridge-type container. The cartridge may vary in length to match the fuse rating of the circuit to be protected so that the wrong size of fuse cannot be fitted. The fuse wire does not deteriorate and is more reliable in operation (Fig. 2).

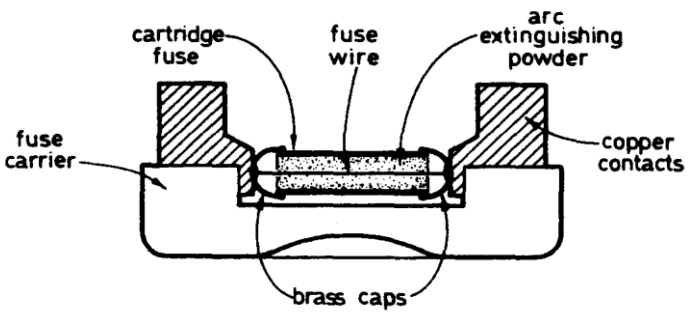



**Fig.2 Cartridge fuse.**

***High Breaking Capacity (H.B.C) Fuse:***

For large currents and where the energy level is high, the high-breaking- capacity (h.b.c.) fuse is used. This is a cartridge-type fuse in which a silver fuse element is connected between two end-contacts of a ceramic tube filled with a special quartz powder. When the fuse blows there is a fusion of the silver vapor produced with the filling powder, so that globules of high-resistance material are formed in the path of the arc, causing it to be extinguished.

This type of fuse is very reliable in performance and can be used when discrimination is required. It does not deteriorate and has a high speed of operation (Fig. 3).

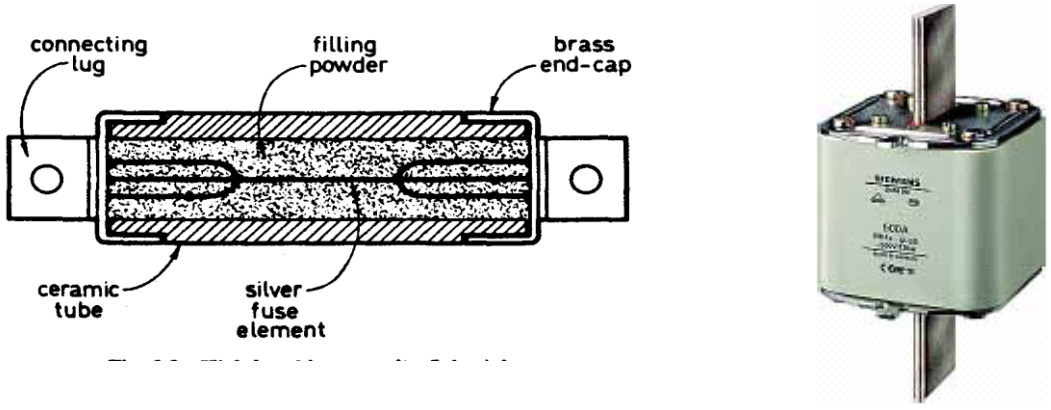



**Fig.3 H.R.C. fuse.**

The characteristic of an HRC fuse is compared with that of an induction relay.

The disadvantage of all types of fuses, of course, is the fact that when they have operated they have to be replaced. The type of fuse chosen to protect a factory circuit

will depend upon the type of load and the circuit conditions. It is important to realize the difference between the current rating of a fuse and its fusing current.
The current rating of a fuse is the current the fuse will carry continuously without blowing or deteriorating.
The rated minimum fusing current is the minimum current at which the fuse will blow in a specified time. This may vary between 1.25 and 2.5 times the current rating.
The relationship between the rated minimum fusing current and the current rating is called the fusing factor:

.

Fusing factor = rated minimum fusing current / current rating

## Classification of LV fuses

In British standard, there are four classes of fuses, depending upon their fusing factors. These are as follows:

***Class P fuses*** These having a fusing factor of 1.25 or less and provide protection . for circuits that cannot withstand even small sustained overloads.

***Class Q fuses*** These fuses are for circuits that can withstand small overcurrents but give protection against higher values of overload. There are two types:

Class Q1—fusing factor between 1.25 and 1.5
Class Q2—fusing factor between 1.5 and 1.75

***Class R fuses*** These fuses have a fusing factor between 1.75 and 2.5 and will protect a circuit against relatively large over- currents only. Their main use is as back-up protection where the normal protection is provided by some other device such as a circuit breaker or a motor overload trip

**According to IEC standard, two classes of LV cartridge fuse are very widely used:**

- for domestic and similar installation ,type gG
- for industrial installations type gG, gM or aM .

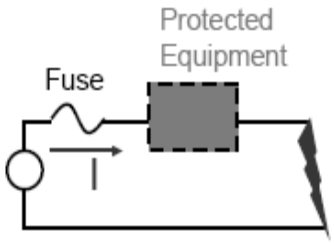
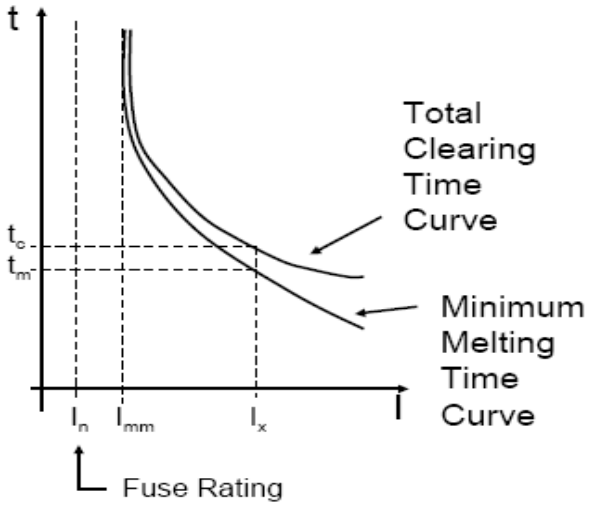



**Fig. 4: zones of fusing and non-fusing for gG and gM fuses.**



Class gG for protection of lighting circuit .While gM and aM for motor protection. class aM fuses protect agains short-circuit currents only, and must t always be associated with another device which protects against overload

As we did with melting time, we can draw a curve to represent the total clearing time as a function of the current.
Following are the main characteristics of a fuse:
• The minimum melting time curve
• The total clearing time curve
• The fuse minimum melting current
• The fuse rating (nominal current) which should not be confused with the minimum melting current.

# Short circuit Current

When short circuit occurs between live conductors ,the short circuit current could flow is known as the " prospective short circuit current " (PSCC) , and the fuse installed to protect against such current must be able break this current >The total amount of energy let-through into the conductors carrying this current is $I^2$ t1.

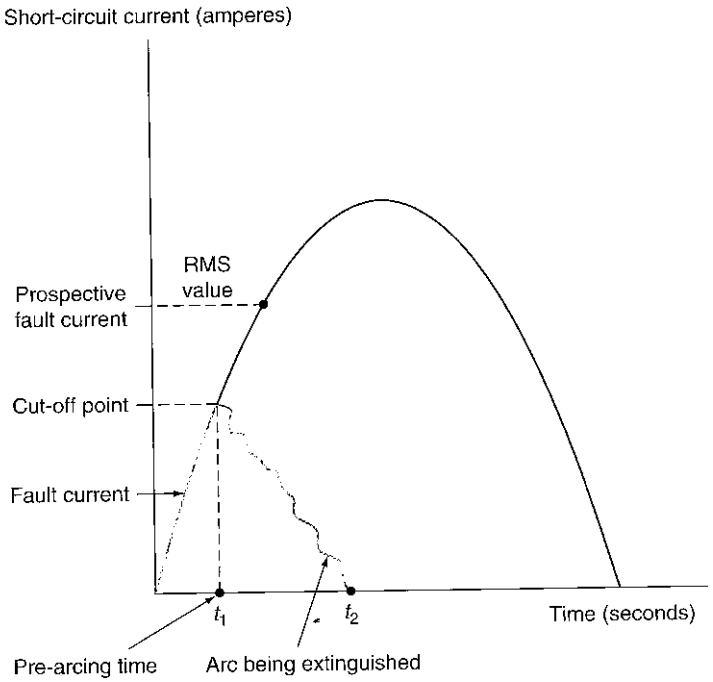



Fig.5 Short circuit current.

**The $I^2t$ factor of the fuse :**

The time of operation of the fuse at high levels of current is inversely proportional to the square of the current during the pre-arcing stage and proportional to the voltage during the arcing stage.
For any conductor, its temperature rise depends on the $I^2t$ factor. This factor can be calculated by empirical formula as:

- For copper conductors

$$I^2\,t = 11.5\,x\,10^4 A^2\,log_{10}\,\frac{273 + \theta_m}{273 + \theta_o} \qquad (1)$$

- For Aluminum conductors

$$I^2\,t = 5.2\,x\,10^4 A^2\,log_{10}\,\frac{273 + \theta_m}{273 + \theta_o} \qquad (2)$$

I = Short circuit current (A)
t = Duration of the short circuit (s)
A = Net cross – sectional area of the conductor ($mm^2$)
$\theta_o$ = Initial temperature of the conductor ($C^o$ )
$\theta_m$ =Final temperature of the conductor

If the pre-arcing $I^2t$ is not exceeded then there will be no deterioration of the fuse performance. This is taken into account when discrimination is required between fuses. If the total $I^2t$ of the smaller fuse is less than the pre-arcing $I^2t$ of the larger fuse then the smaller fuse would operate without causing any deterioration of the larger fuse.

Example : It is proposed to use a No.30 AWG copper wire as a fuse element. If its initial temperature is 50 $C^o$, calculate the following:

(a) Tha $I^2t$ needed to melt the wire (copper melt at1083 $C^o$ ).
(b) The time needed to melt the wire if the short circuit curreny is 30A.

Solution

From tables of wires 30 AWG = 0.0507 $mm^2$

(a) $I^2\,t = 11.5\,x\,10^4\,(0.0507)^2\,log_{10}\,\frac{273+1083}{273+50}$

$= 184 \quad A^2\,s$

(b) For a current of 30 A we obtain:

$I^2t = 184$
$(30)^2\ t = 184$
$t = 0.2$ sec.

# High Voltage Fuses:

High voltage fuses are of three main types:

- Open (drop out) type
- Enclosed type
- Spring type

These types of fuses are shown in Fig.6 ,and are used for voltages up to 33kV.The time current characteristics are shown in Fig.7.

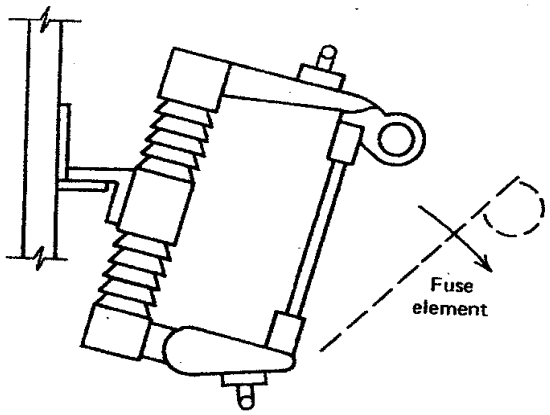
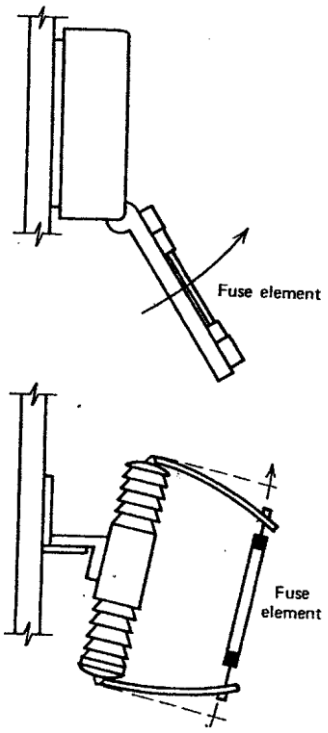



Fig.6 High voltage fuses

Enclosed type




Spring type

**Power system protection Dr.Prof.. Mohammed Tawfeeq**
**Protective Devices: Fuses & Circuit Breakers**

## The Circuit Breakers

### 1.Low Voltage Circuit breakers

.

A 2 pole MCB

A **circuit breaker** is an automatically-operated electrical switch designed to protect an electrical circuit from damage caused by overload or short circuit. Unlike a fuse, which operates once and then has to be replaced, a circuit breaker can be reset (either manually or automatically) to resume normal operation. Circuit breakers are made in varying sizes, from small devices that protect an individual household appliance up to large switchgear designed to protect high voltage circuits feeding an entire city.

**Operation**

***Magnetic circuit breakers*** are implemented using a solenoid (electromagnet) whose pulling force increases with the current. The circuit breaker's contacts are held closed by a latch and, as the current in the solenoid increases beyond the rating of the circuit breaker, the solenoid's pull releases the latch which then allows the contacts to open by spring action.
***Thermal breakers*** use a bimetallic strip, which heats and bends with increased current, and is similarly arranged to release the latch. This type is commonly used with motor control circuits. Thermal breakers often have a compensation element to reduce the effect of ambient temperature on the device rating.

***Thermomagnetic circuit breakers***, which are the type found in most distribution boards, incorporate both techniques with the electromagnet responding instantaneously to large surges in current (short circuits) and the bimetallic strip responding to less extreme but longer-term overcurrent conditions.

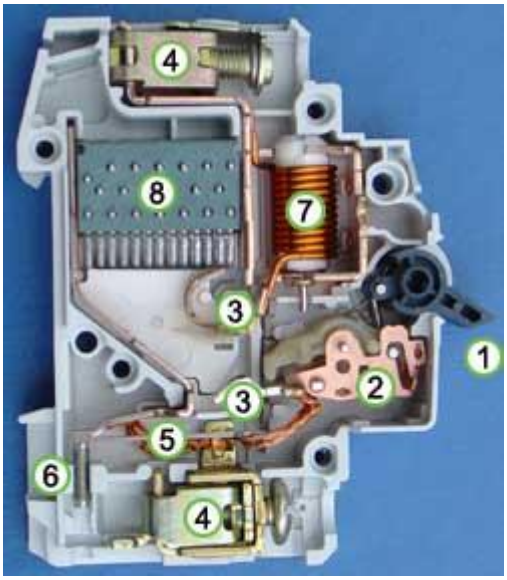
**Types of circuit breaker**

There are many different technologies used in circuit breakers and they do not always fall into distinct categories. Types that are common in domestic, commercial and light industrial applications at low voltage (less than 1000 V) include:

- MCB (Miniature Circuit Breaker)—rated current not more than 100 A. Trip characteristics normally not adjustable. Thermal or thermal-magnetic operation. Breakers illustrated above are in this category.
- MCCB (Moulded Case Circuit Breaker)—rated current up to 1000 A. Thermal or thermal-magnetic operation. Trip current may be adjustable.
- ACB (Air circuit breaker) – rated current up to 4000 A .Thermal and magnetic operation . Trip current adjustaible.

**The MCB Circuit Breaker:**

**Construction :** Figure below shows a single-phase ,single- pole MCB

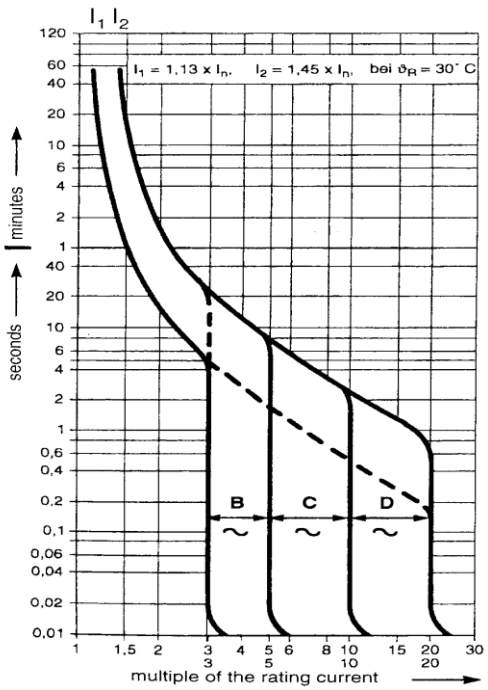


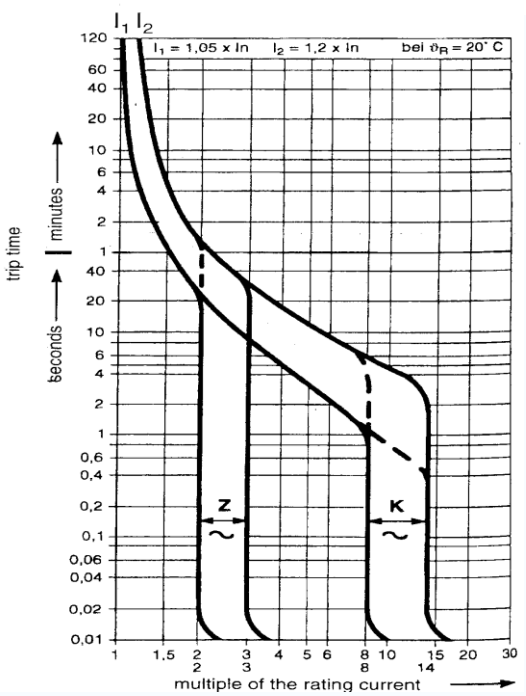

1. Actuator lever - used to manually trip and reset the circuit breaker. Also indicates the status of the circuit breaker (On or Off/tripped). Most breakers are designed so they can still trip even if the lever is held or locked in the on position. This is sometimes referred to as "free trip" or "positive trip" operation.
2. Actuator mechanism - forces the contacts together or apart.
3. Contacts - Allow current to flow when touching and break the flow of current when moved apart.
4. Terminals
5. Bimetallic strip
6. Calibration screw - allows the manufacturer to precisely adjust the trip current of the device after assembly.
7. Solenoid
8. Arc divider / extinguisher

- **Rated current**
  International Standard IEC 60898-1 defines the *rated current I*n of a circuit breaker for household applications as the current that the breaker is designed to carry continuously (at an ambient air temperature of 30 °C). The commonly-available preferred values for the rated current are 6 A, 10 A, 13 A, 16 A, 20 A, 25 A, 32 A, 40 A, 50 A, 63 A, 80 A and 100 A .The circuit breaker is labeled with the rated current in ampere, but without the unit symbol "A". Instead, the ampere figure is preceded by a letter "B", "C" , "D" "K" or "Z" that indicates the *instantaneous tripping current*, that is the minimum value of current that causes the circuit-breaker to trip without intentional time delay (i.e., in less than 100 ms):

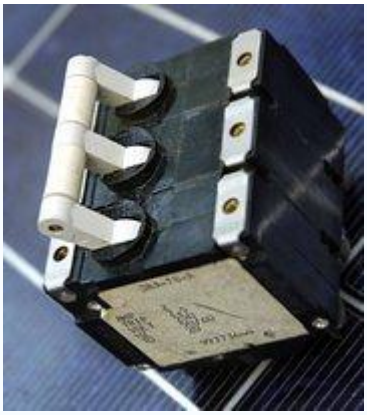
| Type | Instantaneous tripping current |
|---|---|
| B | above 3*I*n up to and including 5*I*n |
| C | above 5*I*n up to and including 10*I*n |
| D | above 10*I*n up to and including 20*I*n |
| K | above 8*I*n up to and including 12*I*n<br><br>For the protection of loads that cause frequent short duration (approximately 400ms to 2s) current peaks in normal operation. |
| Z | above 2*I*n up to and including 3*I*n for periods in the order of tens of seconds.<br><br>For the protection of loads such as semiconductor devices or measuring circuits using current transformers. |

- **Characteristics**



**Common trip breakers**



MCB is also used for 3-phase applications, the figure shows a three- pole common trip breaker for supplying a three-phase device. This breaker has a 5 A rating.

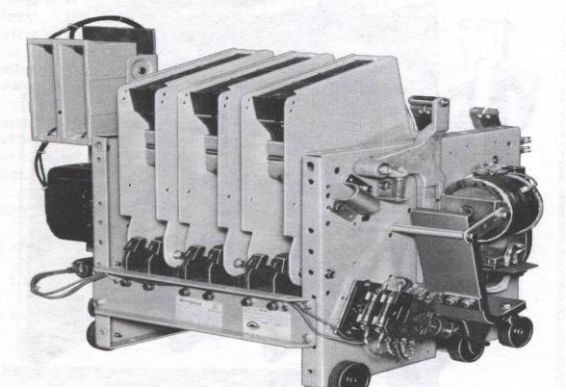
**Molded Case Circuit Breakers (MCCB)**

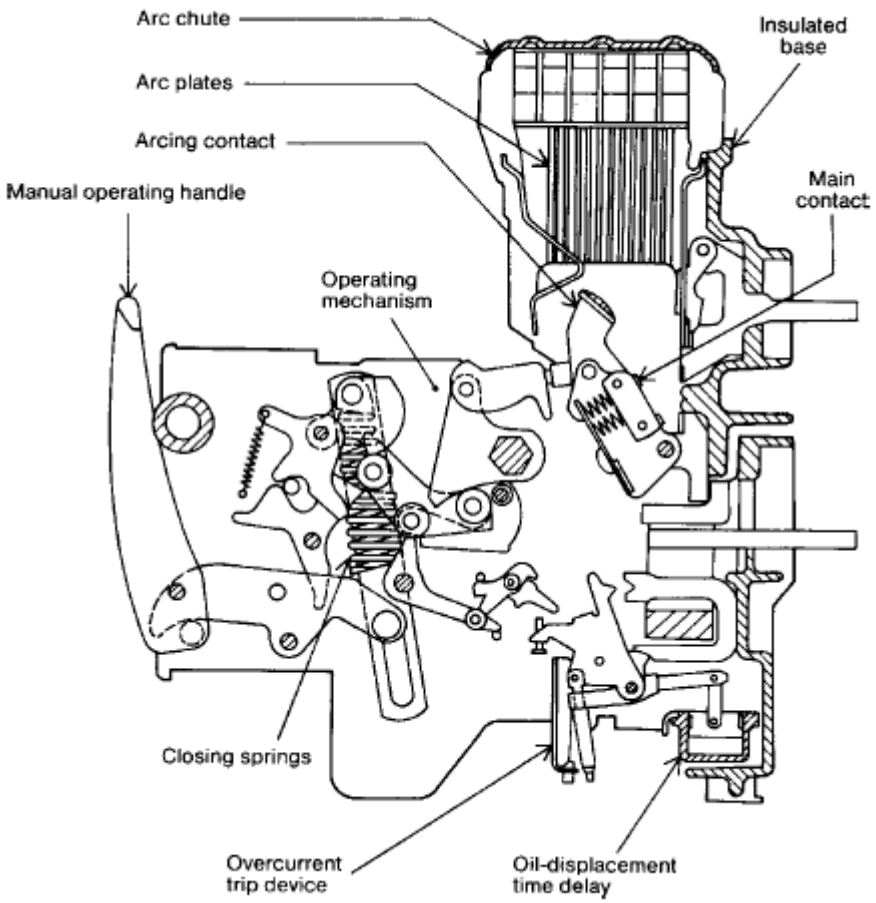
These circuit breakers are mainly used for 3-phase circuits and for currents larger than 100A and up to 1600A. Types of these C.Bs are shown below:

These breakers are used mainly in industrial applications to protect cables and equipment.

**Air Circuit Breaker(ACB)**

This type of circuit breaker is used for heavy current applications up to 6000A.Its construction is shown below :






Typical low-voltage air circuit breaker with magnetic air chutes; breaker in the open position.

**Other types of circuit breakers**.

- Breakers for protections against earth faults too small to trip an overcurrent device:
  - RCD—Residual Current Device (formerly known as a *Residual Current Circuit Breaker*(RCCB)) - detects current imbalance. Does NOT provide overcurrent protection.
  - RCBO—Residual Current Breaker with Overcurrent protection - combines the functions of an RCD and an MCB in one package.
  - ELCB—Earth leakage circuit breaker. This detects earth current directly rather than detecting imbalance. They are no longer seen in new installations for various reasons.

**Power system protection Dr. Prof.Mohammed Tawfeeq**
**Protective Devices: Fuses & Circuit Breakers**

**High Voltage Circuit breakers**

The most important types of H.V circuit breakers are the following:

1- Oil circuit breakers (OCBs) .
2- SF6 circuit breakers .
3-Vacuum circuit break.
4- Air-blast circuit breaker

The triggering action that causes a circuit breaker to open is usually produced by means of an overload relay that can detect abnormal line conditions. For example, the relay coil in Fig.1 is connected to the secondary of a current transformer. The primary carries the line current of the phase that has to be protected. If the line current exceeds a preset limit, the secondary current will cause relay contacts C1, C2 to close. As soon as they close, the tripping coil is energized by an auxiliary dc source. This causes the three main line contacts to open, thus interrupting the circuit.

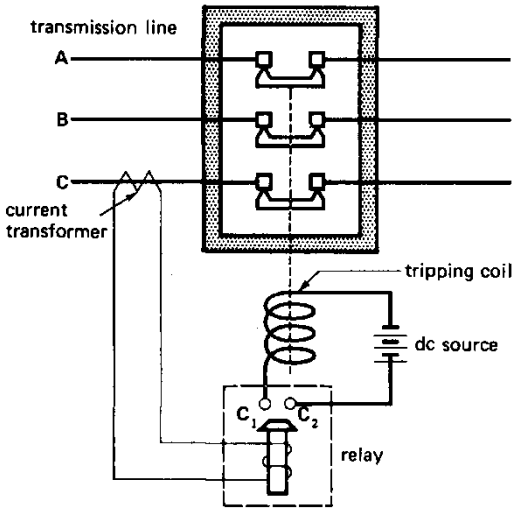



Fig.1

# 1-Oil Circuit Breakers:

**Operation of Oil Circuit Breaker**

The operation of oil circuit breaker: When the current carrying contacts in the oil are separated an arc is established in between the separated contacts. Actually, when separation of contacts has just started, distance between the current contacts is small as a result the voltage gradient between contacts becomes high. This high voltage gradient between the contacts ionized the oil and consequently initiates arcing between the contacts. This arc will produce a large amount of heat in surrounding oil and vaporizes the oil and decomposes the oil in mostly hydrogen and a small amount of methane, ethylene and acetylene. The hydrogen gas cannot remain in molecular form and its is broken into its atomic form releasing lot of heat. The arc temperature may reach up to 5000° K. Due to this high temperature the gas is liberated surround

the arc very rapidly and forms an excessively fast growing gas bubble around the arc. It is found that the mixture of gases occupies a volume about one thousand times that of the oil decomposed. From this figure we can assume how fast the gas bubble around the arc will grow in size. If this growing gas bubble around the arc is compressed by any means then rate of de – ionization process of ionized gaseous media in between the contacts will accelerate which rapidly increase the dielectric strength between the contacts and consequently the arc will be quenched at zero crossing of the current cycle. This is the basic operation of oil circuit breaker. In addition to that cooling effect of hydrogen gas surround the arc path also helps, the quick arc quenching in oil circuit breaker.

**Types of Oil Circuit Breakers**

There are mainly two types of oil circuit breakers available-

- Bulk Oil Circuit Breaker or BOCB
- Minimum Oil Circuit Breaker or MOCB

# Bulk oil circuit breakers

- Bulk oil circuit breaker or BOCB is such types of circuit breakers where oil is used as arc quenching media as well as insulating media between current carrying contacts and earthed parts of the breaker. The oil used here is same as transformer insulating oil.

- Bulk oil circuit breakers are composed of a steel tank filled with insulating oil. In one version (Fig.2), three porcelain bushings channel the 3-phase line currents to a set of fixed contacts. Three movable contacts, actuated simultaneously by an insulated rod, open and close the circuit. When the circuit breaker is closed, the line current for each phase penetrates the tank by way of one porcelain bushing, flows through the first fixed contact, the movable contact, the second fixed contact, and then on out by a second bushing.

If an overload occurs, the tripping coil releases a powerful spring that pulls on the insulated rod, causing the contacts to open. As soon as the contacts separate, a violent arc is created, which volatilizes the surrounding oil. The pressure of the hot gases creates turbulence around the contacts. This causes cool oil to swirl around the arc, thus extinguishing it.

# Minimum Oil Circuit breaker (MOCB)

As the volume of the oil in bulk oil circuit breaker is huge, the chances of fire hazard in bulk oil system are more. For avoiding unwanted fire hazard in the system, one important development in the design of oil circuit breaker has been introduced where use of oil in the circuit breaker is much less than that of bulk oil circuit breaker. It has been decided that the oil in the circuit breaker should be used only as arc quenching media not as an insulating media. Then the concept of **minimum oil circuit breaker** comes.

These circuit breakers contain minimum quantity of oil. The three phases are separated into three chambers as shown in Fig.3. Unlike bulk oil circuit breaker, the insulating oil is available only in interrupting chamber.

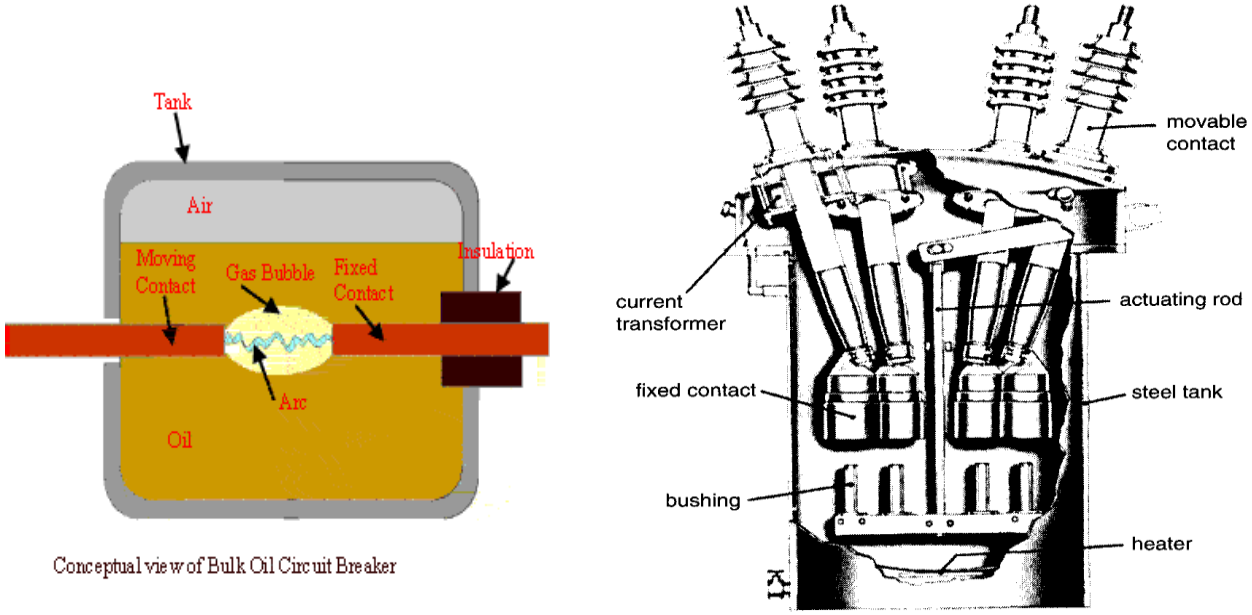



Fig. 2 Bulk oil circuit breaker

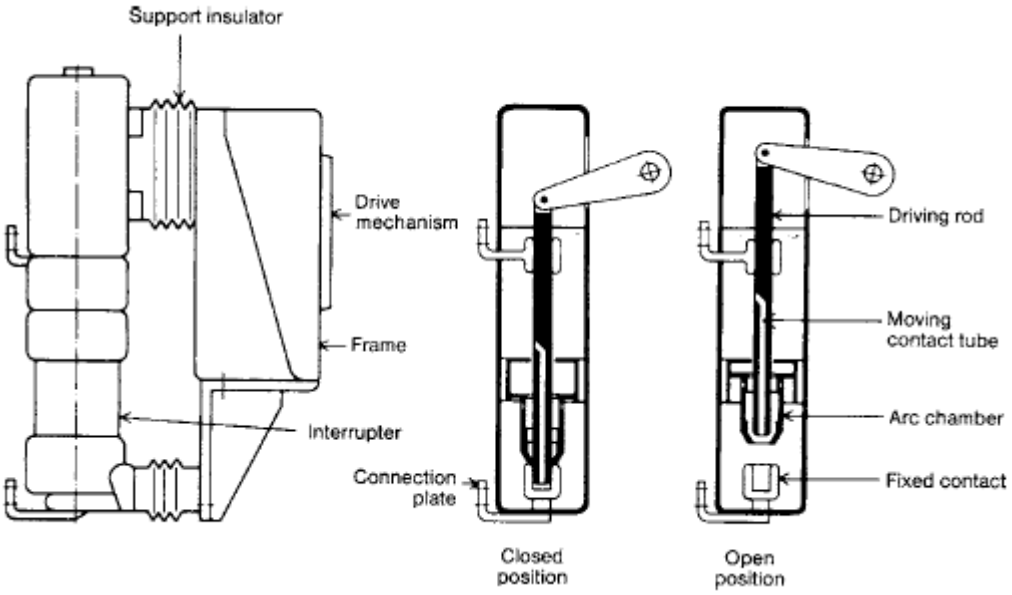



Fig.3 Outline and interrupter details of a 15-kV, 3-pole minimum-oil circuit breaker.

## 2 - SF6 Circuit Breakers

These totally enclosed circuit-breakers, insulated with SF6 gas, are used whenever space is available. Several characteristics of SF6 circuit breakers can explain their success:

- Simplicity of the interrupting chamber which does not need an auxiliary breaking chamber;
- Autonomy provided by the puffer technique;
- The possibility to obtain the highest performance, up to 63 kA, with a reduced number of interrupting chambers;
- Short break time of 2 to 2.5 cycles;
- High electrical endurance, allowing at least 25 years of operation without reconditioning;
- Possible compact solutions when used for GIS or hybrid switchgear;
- Integrated closing resistors or synchronized operations to reduce switching overvoltages;
- Reliability and availability;
- Low noise levels.

The reduction in the number of interrupting chambers per pole has led to a considerable simplification of circuit breakers as well as the number of parts and seals required. As a direct consequence, the reliability of circuit breakers improved.

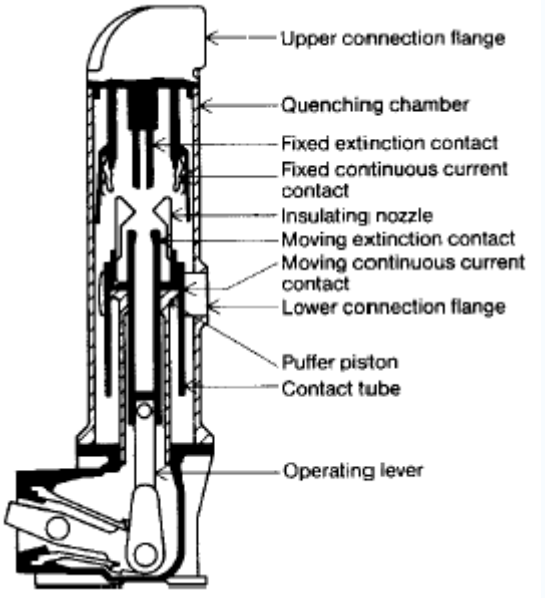


Fig.4 Section of a SF6 puffer-piston indoor circuit breaker, 23 kV.

Fig.5 A 1200A 3-pole 115,000 V break

**Disadvantages**

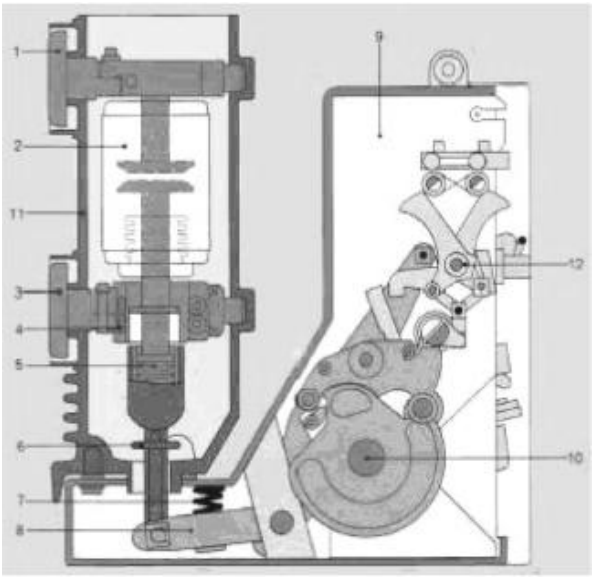
The main disadvantages of SF6 circuit breakers are :
1. SF6 breakers are costly due to the high cost of SF6.
2. Since SF6 gas has to be reconditioned after every operation of the breaker, additional equipment is required for this purpose.

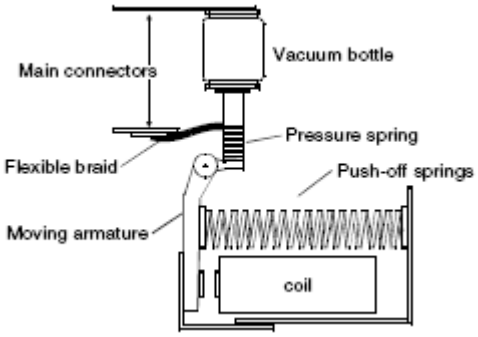
**Applications.**

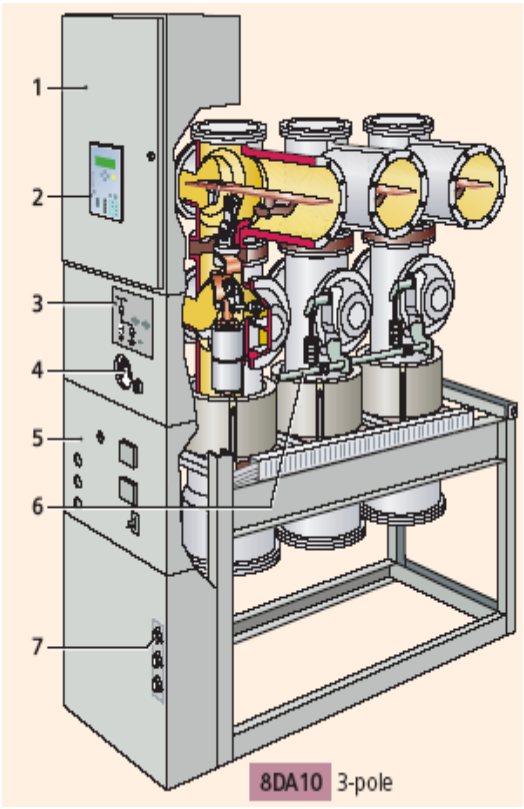
A typical SF6 circuit breaker consists of interrupter units each capable of dealing with currents up to 60 kA and voltages in the range of 50—80 kV. A number of units are connected in series according to the system voltage. SF6circuit breakers have been developed for voltages 115 kV to 230 kV, power ratings 10 MVA to 20 MVA and interrupting time less than 3 cycles.

# 3. Vacuum Circuit Breakers.

These circuit breakers operate on a different principle from other breakers because there is no gas to ionize when the contacts open. They are hermetically sealed; consequently, they are silent and never become polluted (Fig.6). Their interrupting capacity is limited to about 30 kV. For higher voltages, several circuit breakers are connected in series.






1 Upper connection
2 Vacuum interrupter
3 Lower connection
4 Roller contact (swivel contact for 630 A)
Contact pressure spring
6 Insulated coupling rod
7 Opening spring
8 Shift lever
9 Mechanism housing with spring operating mechanism
10 Drive shaft
11 Pole tube
12 Release mechanism

Fig.6: VCB Circuit breaker

## 4. Air-Blast Circuit Breakers:

These circuit breakers interrupt the circuit by blowing compressed air at supersonic speed across the opening contacts. Compressed air is stored in reservoirs at a pressure of about 3 MPa (435 psi) and is replenished by a compressor located in the substation. The most powerful circuit breakers can typically open short-circuits currents of 40 kA at a line voltage of 750 kV in a matter of 3 to 6 cycles on a 50 Hz line. The noise accompanying the air blast is so loud that noise-suppression methods must be used when the circuit breakers are installed near residential areas. Fig.7 shows a typical 1-phase contact module of an air-blast circuit breaker.

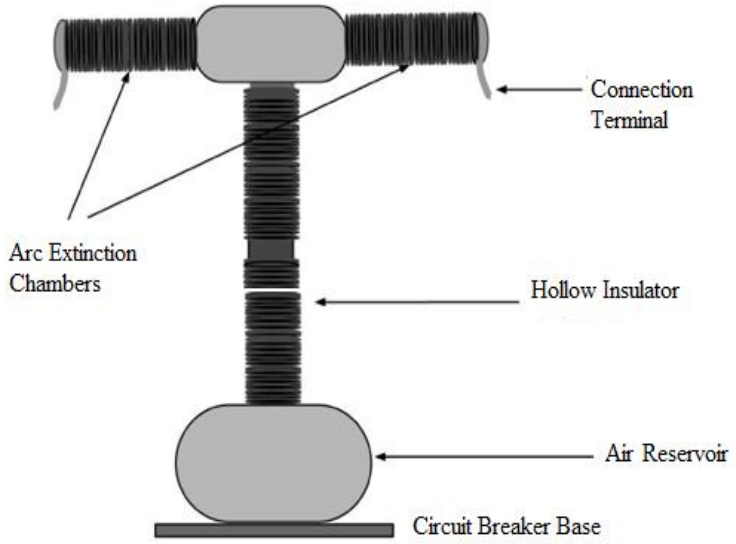



Fig.7 A typical 1-phase contact module of an air-blast circuit breaker.

## Types of Air-Blast Circuit Breakers

Air-blast circuit breakers are manufactured in three technologies:

1. **Axial-blast type:** in which the air-blast is directed along the arc path as shown in Fig.8 (a)
2. **Cross-blast type**: in which the air-blast is directed at right angles to the arc path as shown in Fig.8 (b).
3. **Radial-blast type**: in which the air-blast is directed radially as shown in Fig.8 (c).

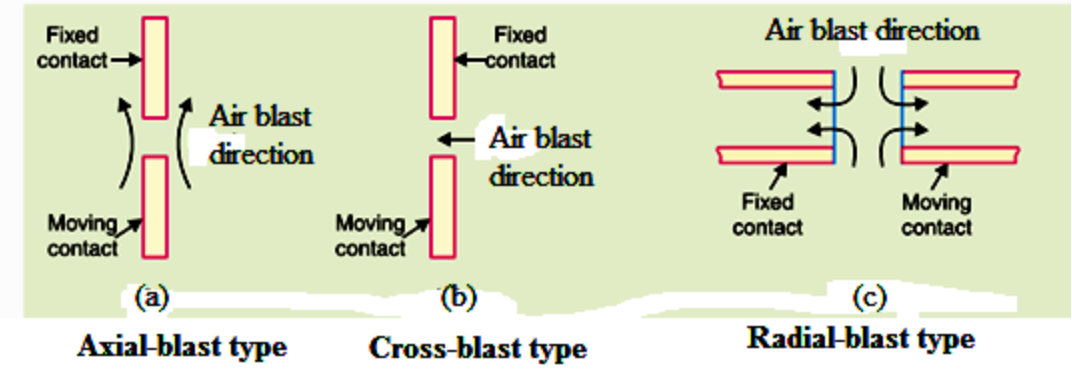



Fig.8 shows a typical 3-phase air-blast circuit breaker. Each phase is composed of three contact modules connected in series.

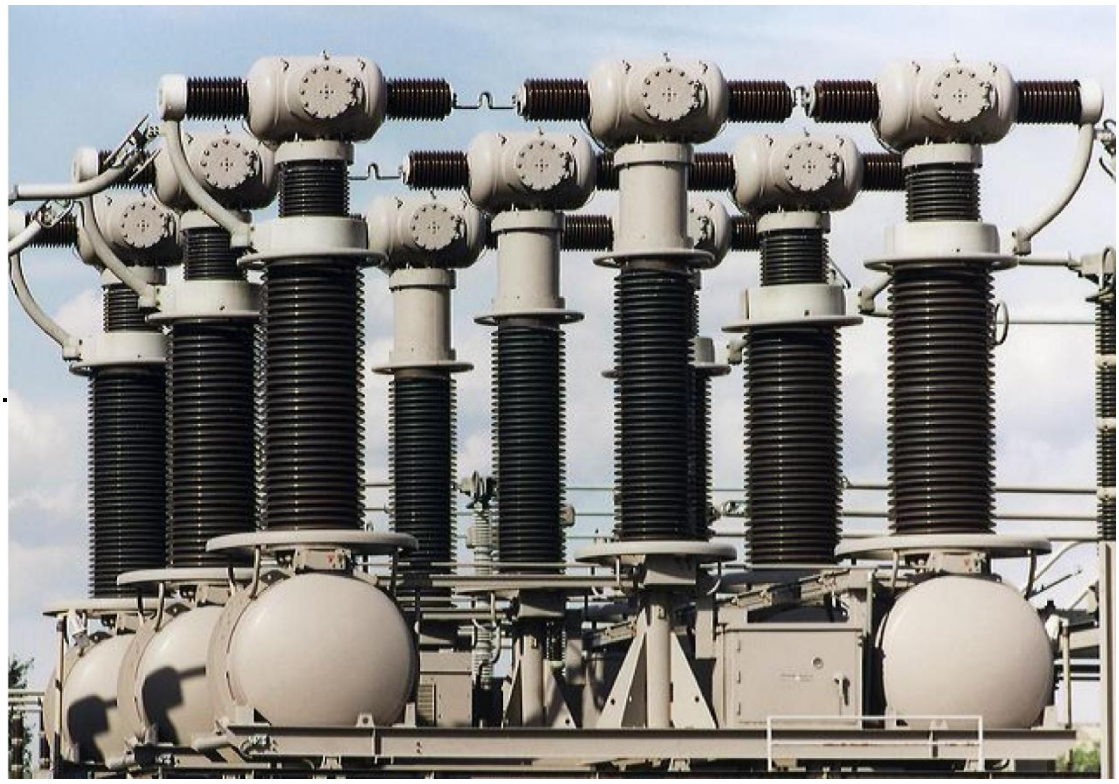
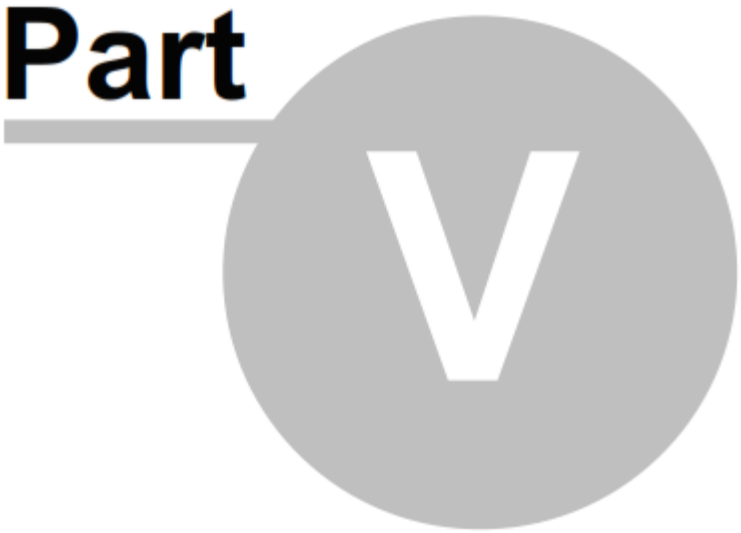


Fig.9 Actual view for air blast circuit breaker in a 400kV substation.




# Power System Protection

# Overcurrent Protective Relays

**Dr.Professor Mohammed Tawfeeq Lazim Alzuhairi**

**Power system protection** **Dr.Mohammed Tawfeeq**

**Overcurrent Protective Relays**

# Overcurrent relays

Overcurrent relaying is the simplest and cheapest type of protection used for protection of lines, transformers, generators and motor.

# Overcurrent relays Types

Based on operating time characteristics, normally defined by the time vs. current curve (or T-I curve), there are three main types of overcurrent relays:

- Instantaneous
- Time-dependent ⟹ Definite time or Inverse time
- Mixed ⟹ Definite time + Inverse time

# 1. Instantaneous Overcurrent Relays(50,50N)

These relays operate without time delay, so they are called instantaneous units(operating time= 0.1 second). The simplest form of these relays is the magnetic attraction types shown in Fig.1. Solid - State, digital and numerical overcurrent relays also available.

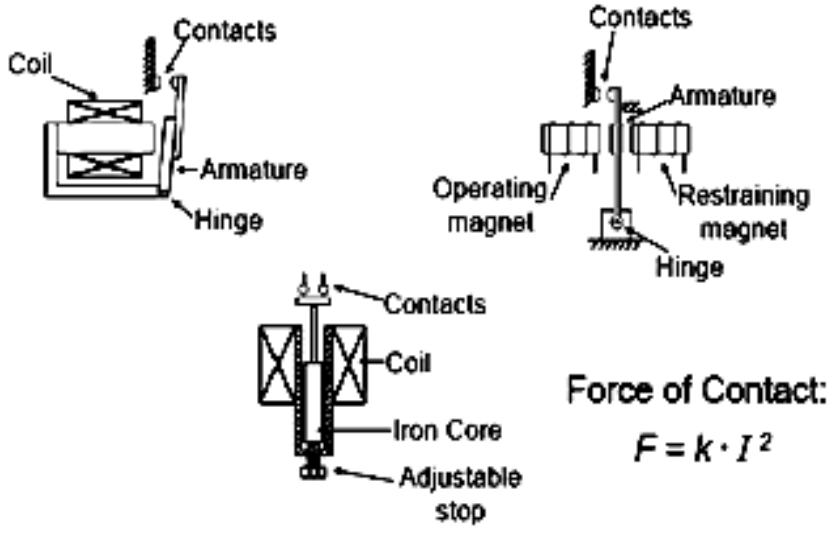


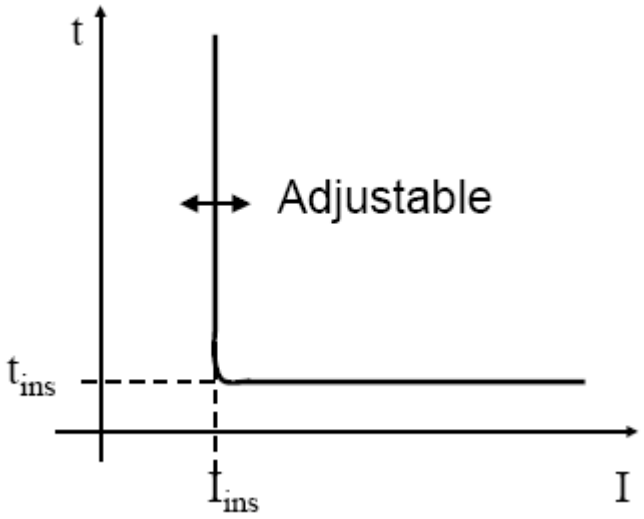

Fig.1

- The pickup current (threshold) is adjustable and the user can choose the setting from a relatively large range.

- **Pickup Current Setting**
  - Taps in the Relay Current Coil
  - Air-Gap Adjustment
  - Spring Adjustment

- **Features of Electromechanical 50 Elements**
  - Suitable for AC and DC Systems
  - Operation Time Less Than 3 Cycles

## Instantaneous Curve (50)




**50 (ANSI)**

Only current is adjustable - Time $t_{ins}$ < 3 Cycles

# 2. Time Overcurrent Relays

Time overcurrent relays operate with a time delay. The time delay is adjustable. The minimum current at which the relay operates (pick up current) is also adjustable.

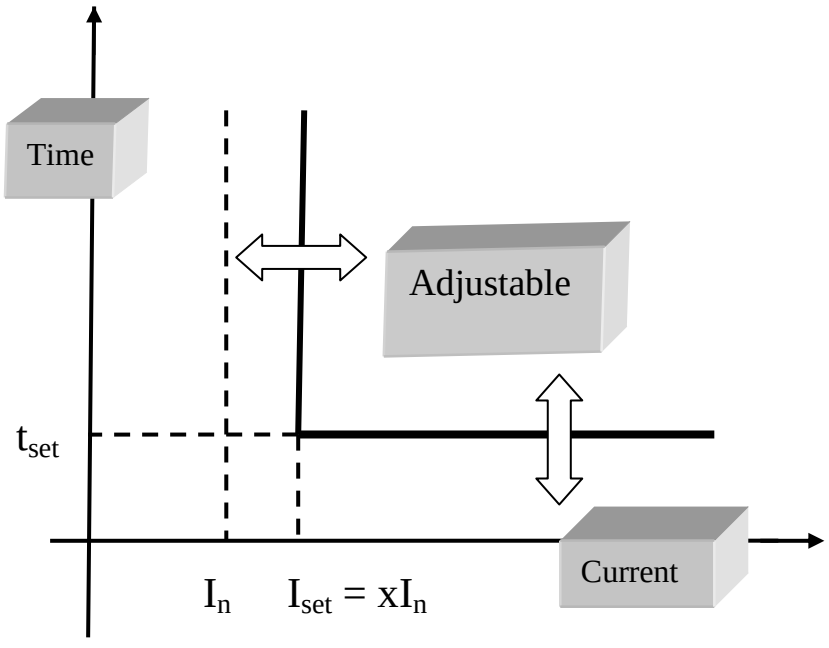
There are five different types of time over-current relays. Their time-current characteristic curves are:

- *Definite time*
- *Inverse-time:*
  - *Moderately inverse*
  - *Inverse (Normal)*
  - *Very inverse*
  - *Extremely inverse*

## 2.1 Definite-Time Overcurrent Relays

The definite-time relay operates with some delay. This delay is adjustable (as well as the current threshold).

**Definite - Time Curve (50)**



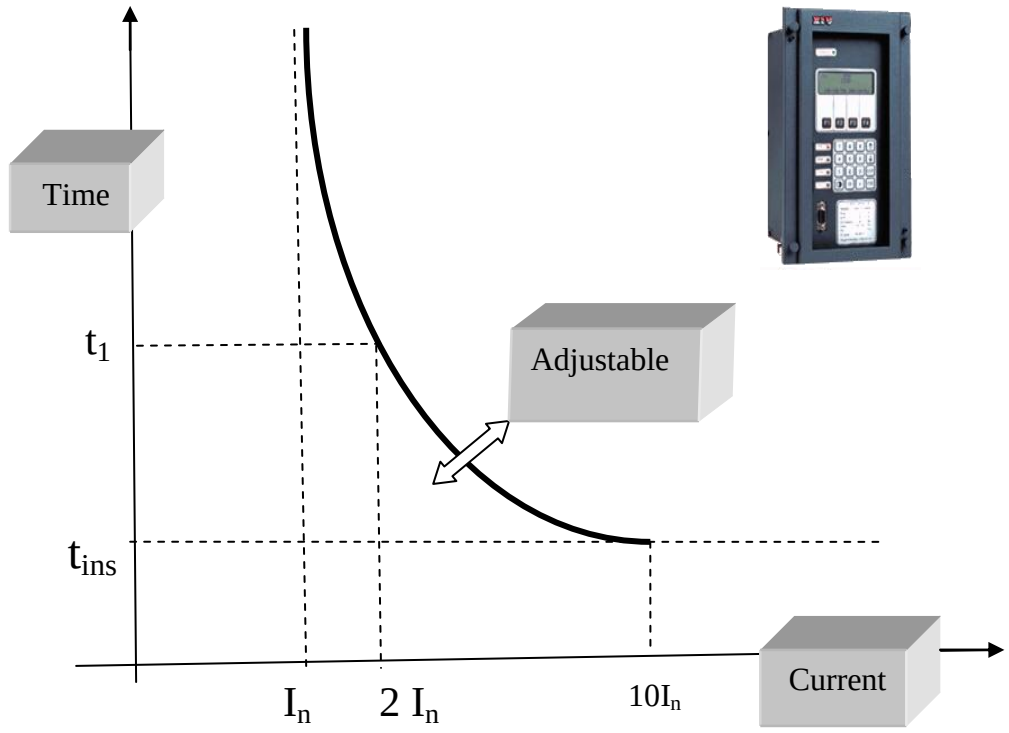

Definite – Time Curve (50 ).

# 2.2 Inverses-Time Overcurrent Relays

This type of relay have an operating time depending on the value of the current, generally with an inverse characteristic, the operation time of the relay is smaller as the current gets larger.

These relays also have two settings: the pick-up current and the curve level. In early electromechanical relays the curve is set by means of a dial. Thus, the setting is called the "time dial setting - TDS".

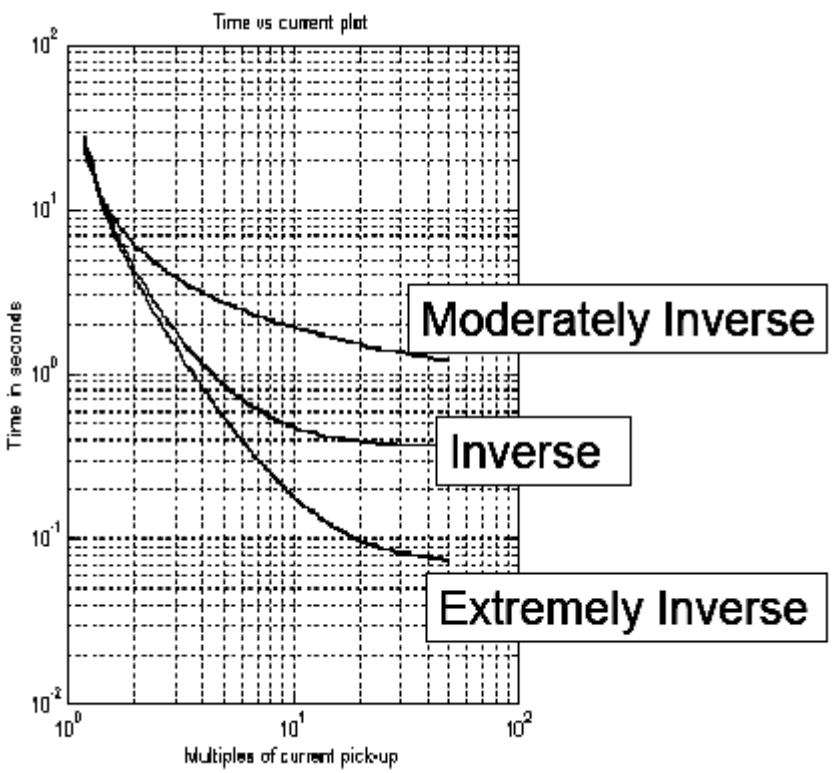
## Inverse - Time Curve (51)




Inverse time curve (51)

# Degrees of Inverse Curves

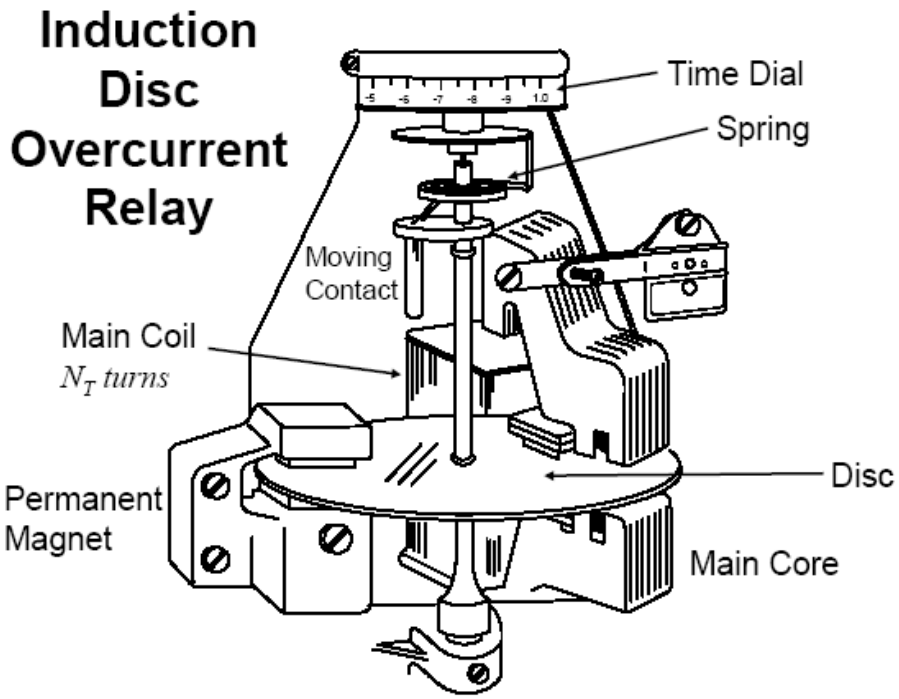
■The most common three types of curves used are, Normal inverse (NI), Very inverse (VI) and Extremely inverse (EI).



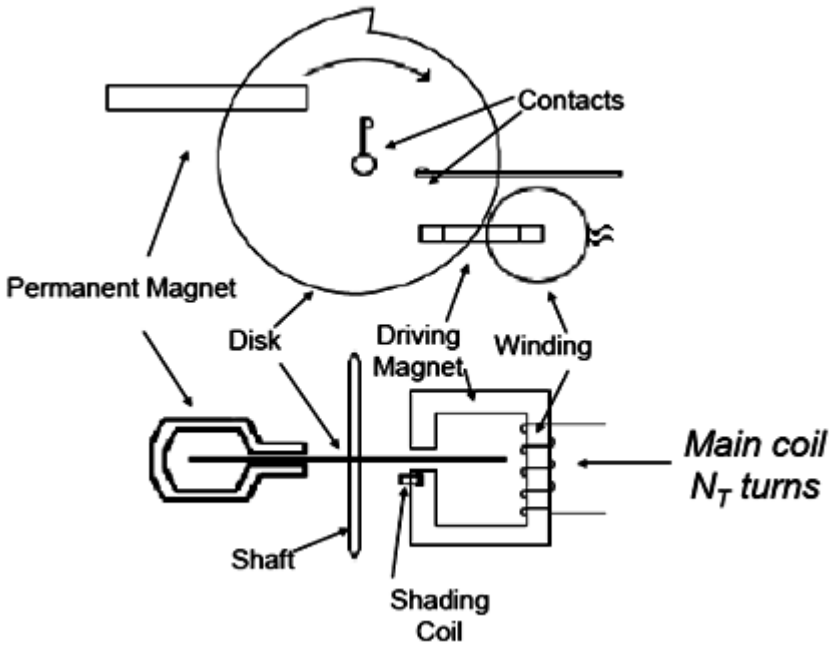

IEEE does not specify coefficients in the standard curve equation. Thus, each manufacturer's curve is similar. But different IEC curves are standardized

# Typical Inverse-Time Overcurrent Relay Elements

## 1. Induction disc overcurrent relay.




## 2. Shaded-Pole Induction 51 Element



# Overcurrent Relay Setting

- 50 Elements: Pickup Setting
- 51 Elements Pickup setting
  - ❖ Time delay setting
  - ❖ definite time: time setting
  - ❖ inverse time: curve selection

# Selecting an Overcurrent Relay Time Curve According to American Standrd

Time-overcurrent relays (ANSI 51 relays) have two basic settings:

the pickup current and the time delay settings.

The process for determining the time delay setting involves:

(1) Calculation of a time delay value in definite-time overcurrent elements

(2) Selection in inverse-time overcurrent elements of a time-current curve from a family of curves.

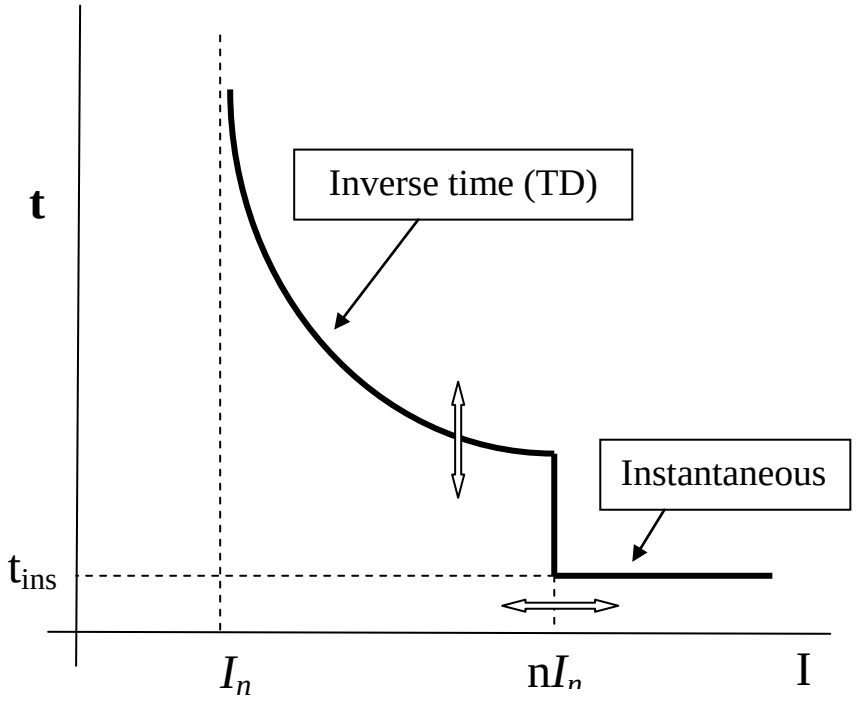
***Note: Instantaneous over current (50) elements have only one setting: the pickup current.***

# 2.3 Mixed Curves Overcurrent Relays

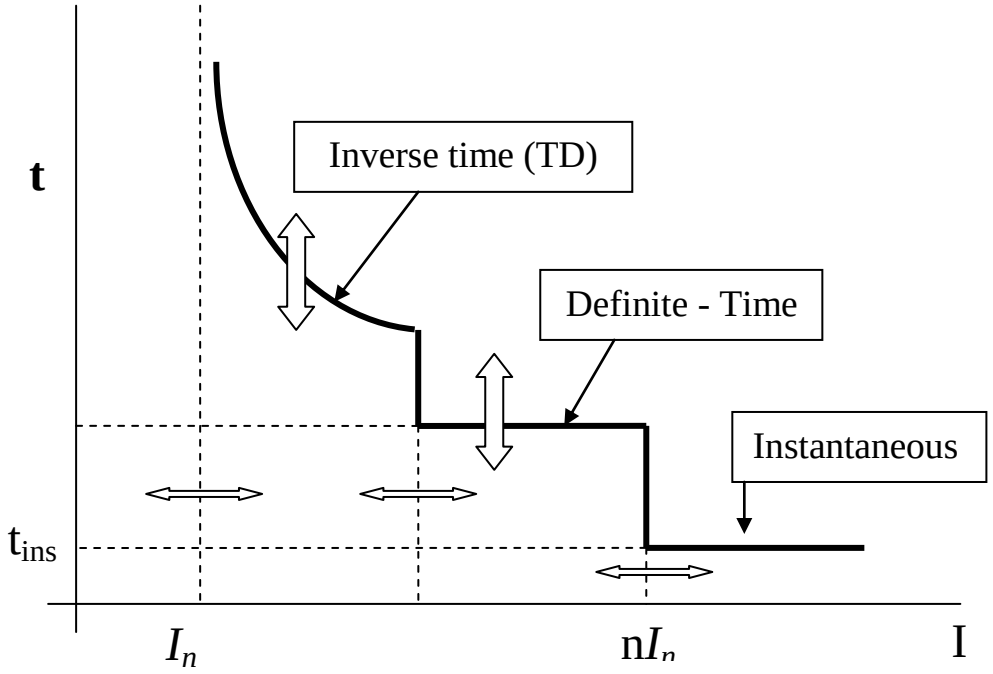
Mixed curves have all the advantages of the different types of overcurrent relays. As the OC elements are built as separate units, we may implement the overcurrent protection principles using:

- a combination of instantaneous and definite-time elements or
- a combination of instantaneous and inverse-time elements.
- a combination of instantaneous, definite-time and inverse-time elements.
- a combination of definite-time and inverse-time elements(IDMT).

## 2.3.1 Mixed Curves (Inverse-Time + Instantaneous)



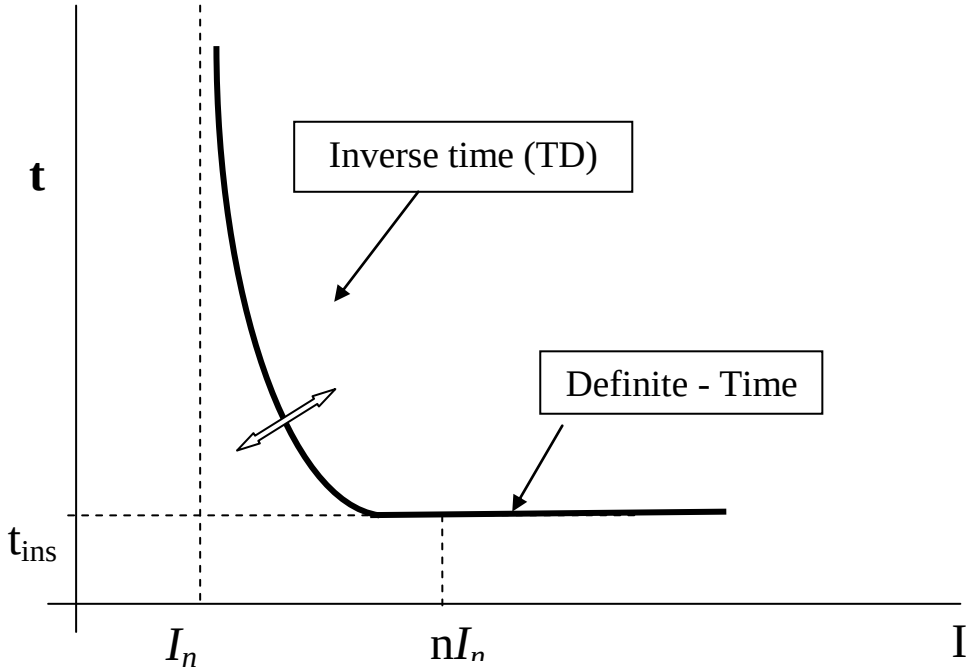
## 2.3.2 Mixed Curves (Inverse-Time +Definite -Time + Instantaneous)




**Note: This type of characteristic is mainly used in digital relays.**

## 1.3.3 Mixed Curves (Inverse-Time +Definite -Time) IDMT – Characteristics

The most commonly used type of relay is the inverse definite with minimum time lag relay (IDMT) in which inverse characteristic plus definite time characteristic are used.
In this relay, the operating time is approximately inversely proportional to the fault current near pickup value and become substantially constant slightly above the pick up value of the relay. This characteristic is shown in the following figure.



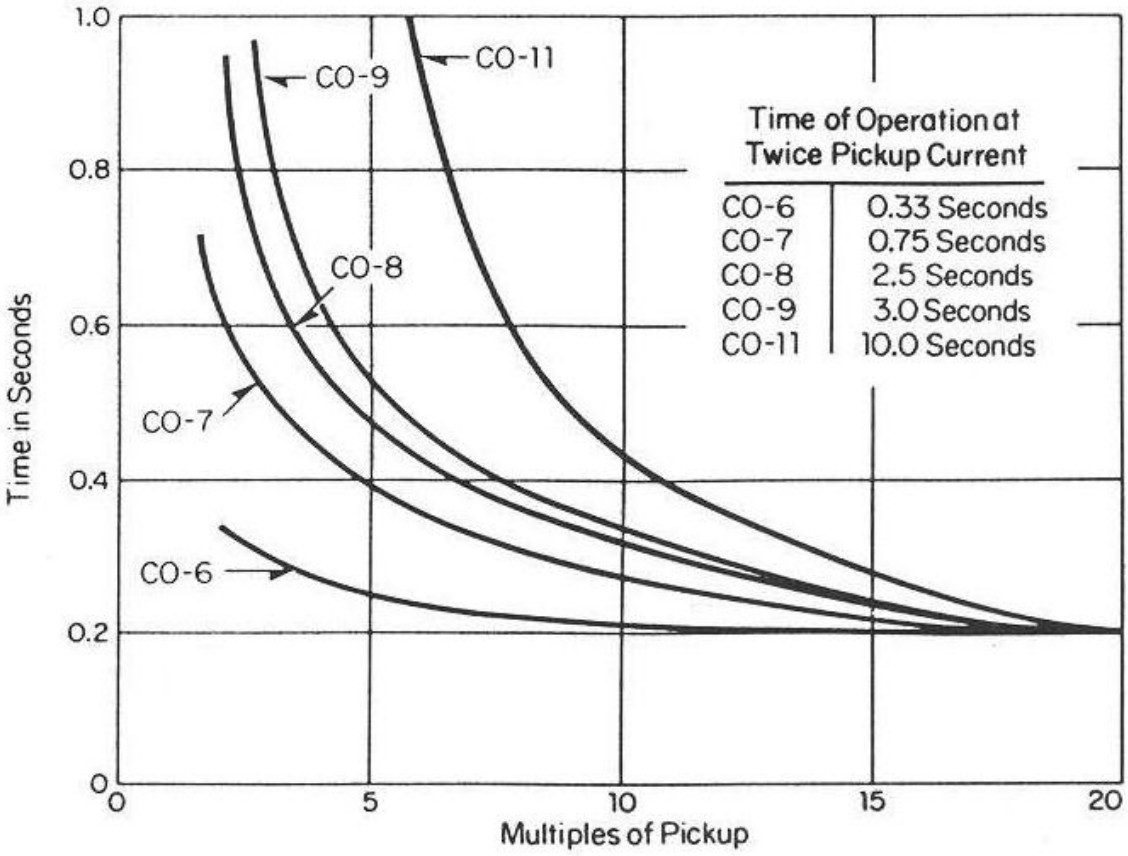

- This characteristic can be achieved using a core of electromagnet which gets saturated for currents slightly greater than the pickup current.
- Wattmetric and shaded pole relays of induction type can be used to obtain this characteristic.

# Standard Time and Inverse definite minimum time (IDMT) Relay Characteristics

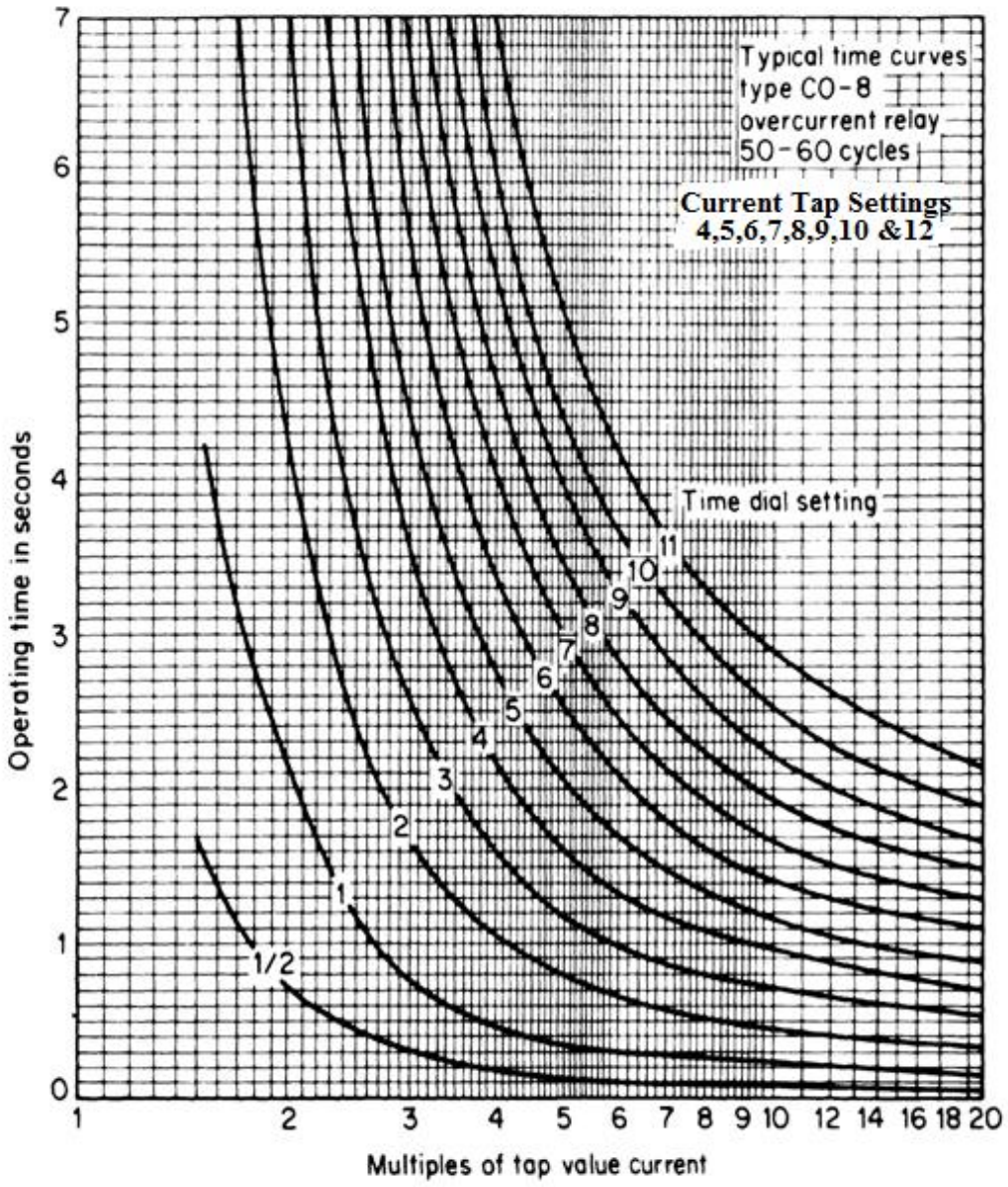
## 1. American Standard

- In American standard there are five different types of time overcurrent relay. Their time-current characteristic curves are:
  - *Definite minimum, CO-6*
  - *Moderately inverse, CO-7*
  - *Inverse, CO-8*
  - *Very inverse, CO-9*
  - *Extremely inverse, CO-11*

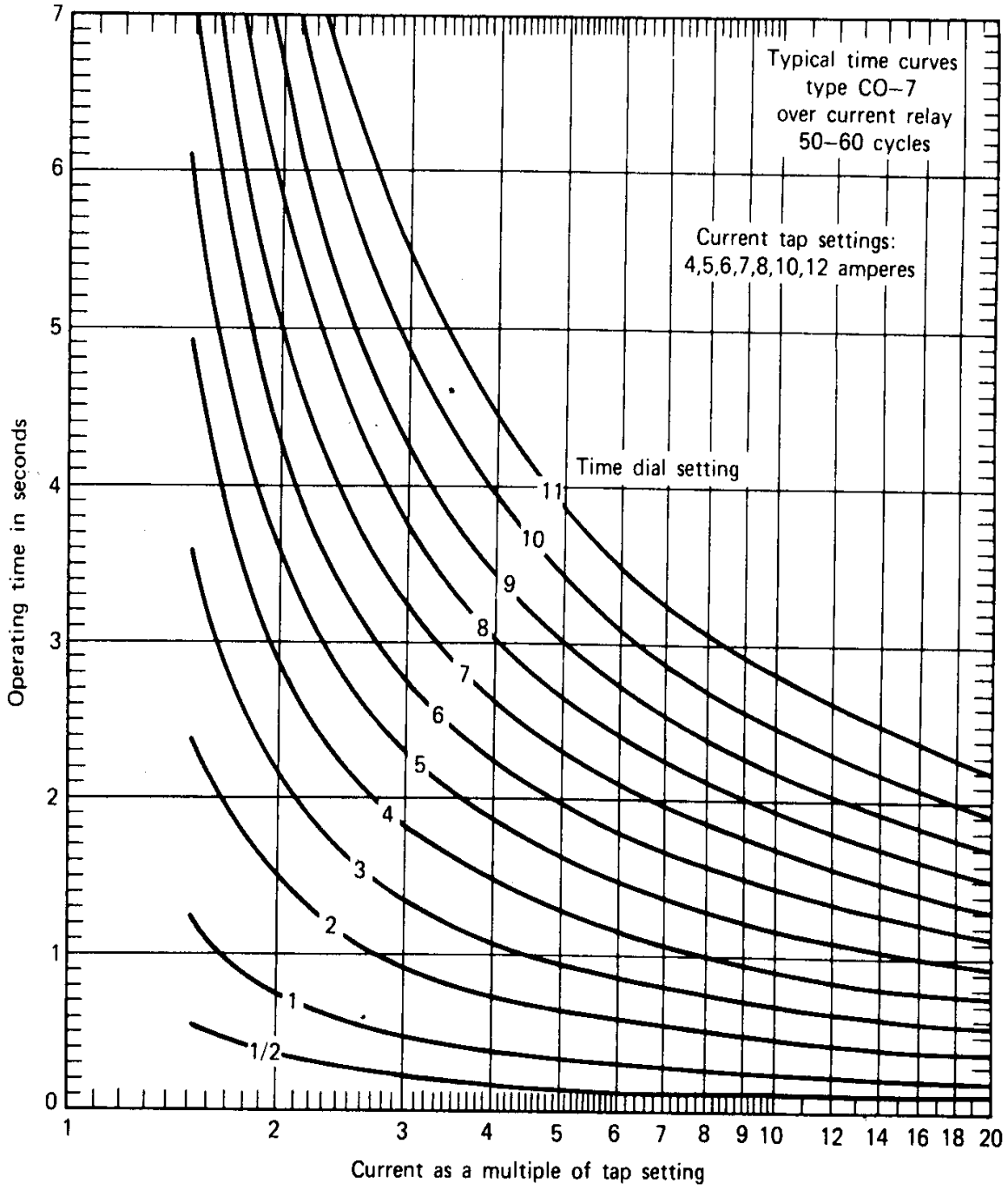
These time-current characteristics are compared in Figure below. *The time lever settings are selected so that all relays operate in 0.2 sec at 20 times the tap setting.*



## Typical time curves for CO-8 American overcurrent relay (normal inverse).



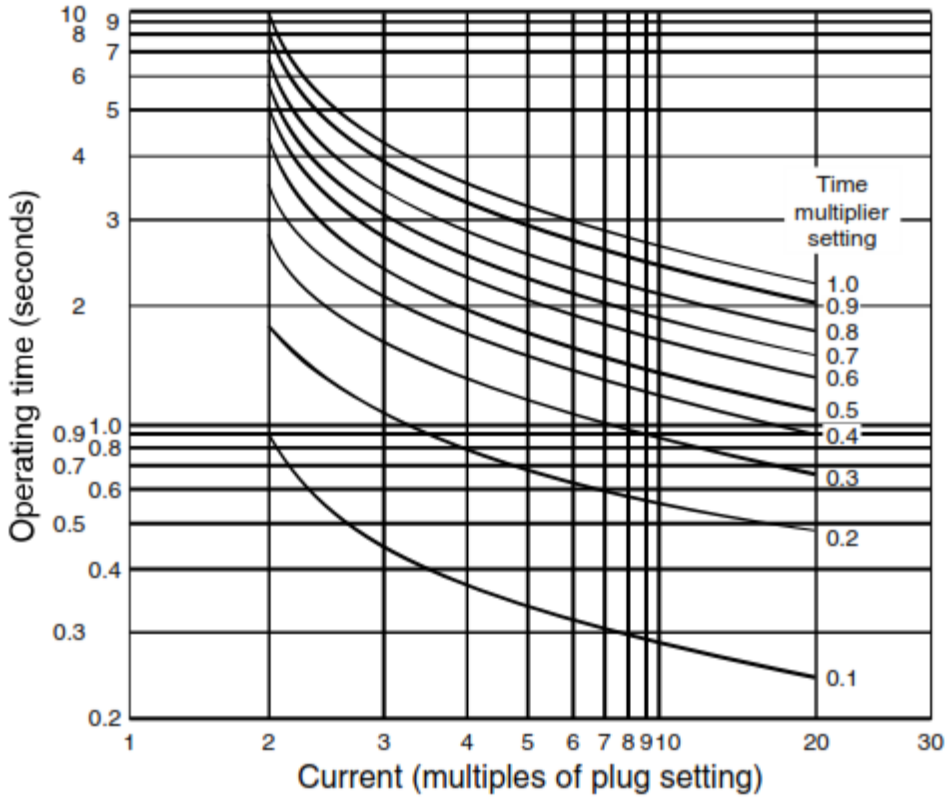
## Typical time curves for CO-7 American overcurrent relay (moderate inverse).



## 2. IEC and British Standards

**In IEC and BS Standards , we have three curves that one can use :**

**(a) The typical time curves for standard British Standard (BS142) and IEC Standard overcurrent relay (normal inverse). For: TMS= 0.1- to -1.0. shown below:**



**(b) The typical time curves for standard BS and IEC overcurrent relay(normal inverse).TMS=1.**

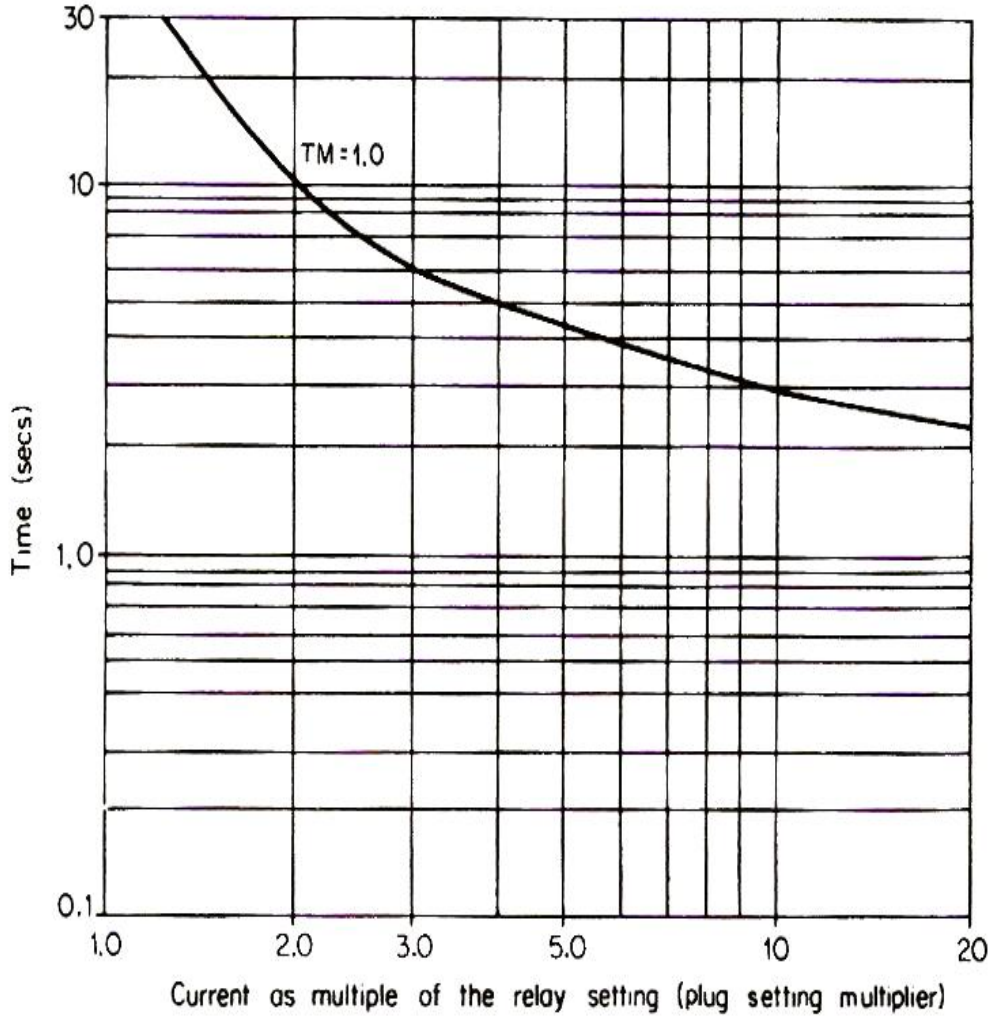



Figure- 1A

**(c ) OR the above figure can be given as:**

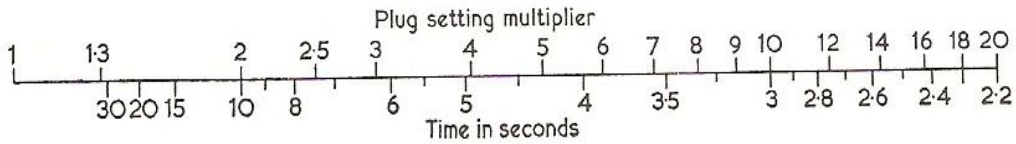



Figure – 1B

# Curve Equations

**1. The typical time curves for CO-8 American overcurrent relay(normal inverse) characteristics can be approximated by the following equation.**

$$t_{relay} = TD \left[\frac{5.95}{M^2-1} + 0.18\right]$$

Where TD = Time delay

$$M = \frac{I}{I_{pickup}}$$

$$t_{relay} = operating\ time\ of\ the\ relay$$

$$I_{pickup} = Relay\ pick\ up\ current$$

**2. The typical time curves for IEC and BS standards overcurrent relay(normal inverse) characteristics can be approximated by the following equation.**

$$t_{relay} = \frac{0.14 \times TMS}{\left(\frac{I_F}{CTR \times PS}\right)^{0.02} - 1}$$

Where : TMS = Time multiplier setting

CTR = Current transformer ratio

PS = Plug setting

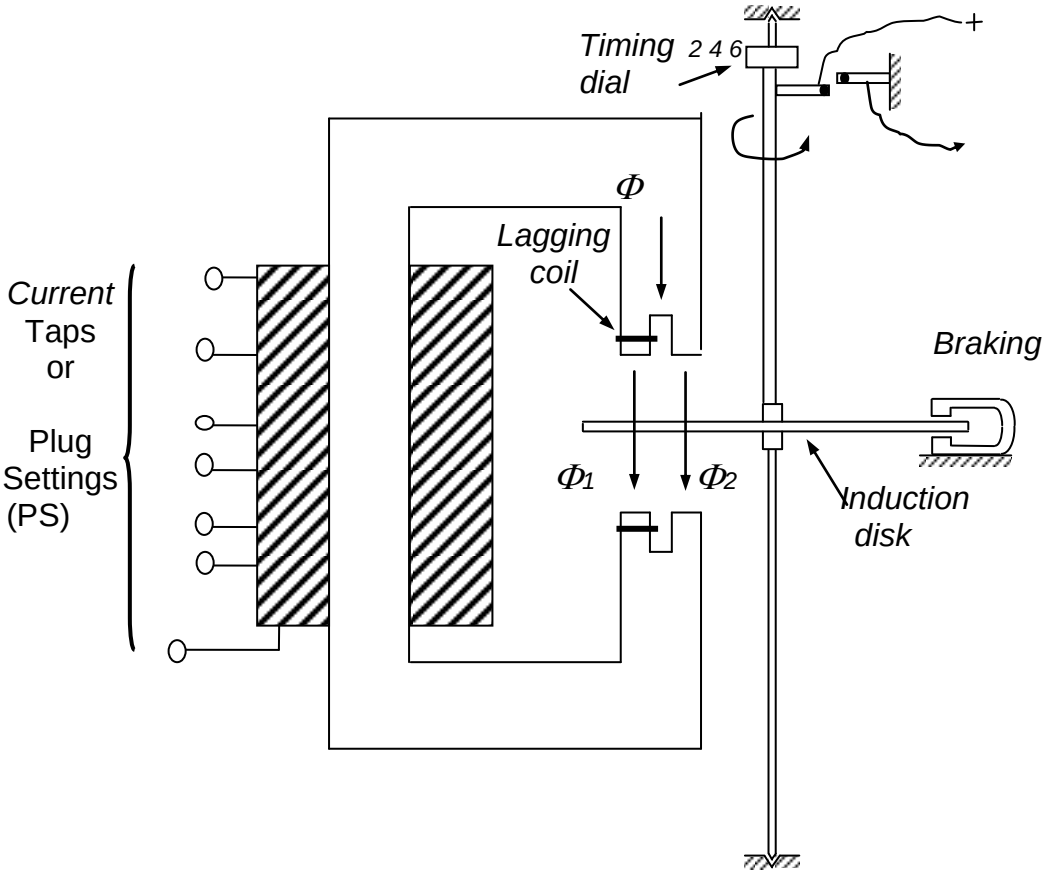
$I_F$ = Fault primary current

# Notes on IEC and BS Standards

## • Meaning of the Plug Setting (PS) and Time multiplier Setting (TMS) in Overcurrent Relays.

**The working principle of an inverse time overcurrent relay is depicted in figure below.**

- **The current to be controlled feeds a coil with multiple taps which allow the pick up current setting - Plug setting (PS).**
- **The generated magnetic field makes the disc rotate with a speed proportional to the current.**
- **A timing dial allows the adjustment between contacts and hence sets the operating time –Time dial setting.**
- **The braking magnet lessens the rotating speed and acts as an opposing force to the rotation. Varying the magnetization, different tripping curves can be achieved.**



## The following Table gives the equivalent names for overcurrent relay setting in both IEC and American Standards

| IEC & BS standard | American Standard |
|---|---|
| Plug Setting (PS) | Current Tap Setting (CTS) |
| Time Multiplier Setting (TMS) | Time Dial Setting (TDS) |

***Example*:** Calculate the plug setting and time multiplier setting for an IDMTL relay on the following network so that it will trip in 2.4 s (see Figure 1).The relay characteristic is shown in Figure2.The C.T. setting is 100/5 A and the fault current is 1000 A.

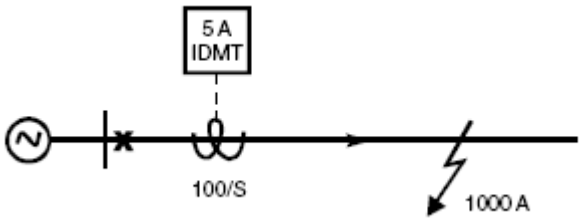



Figure 1

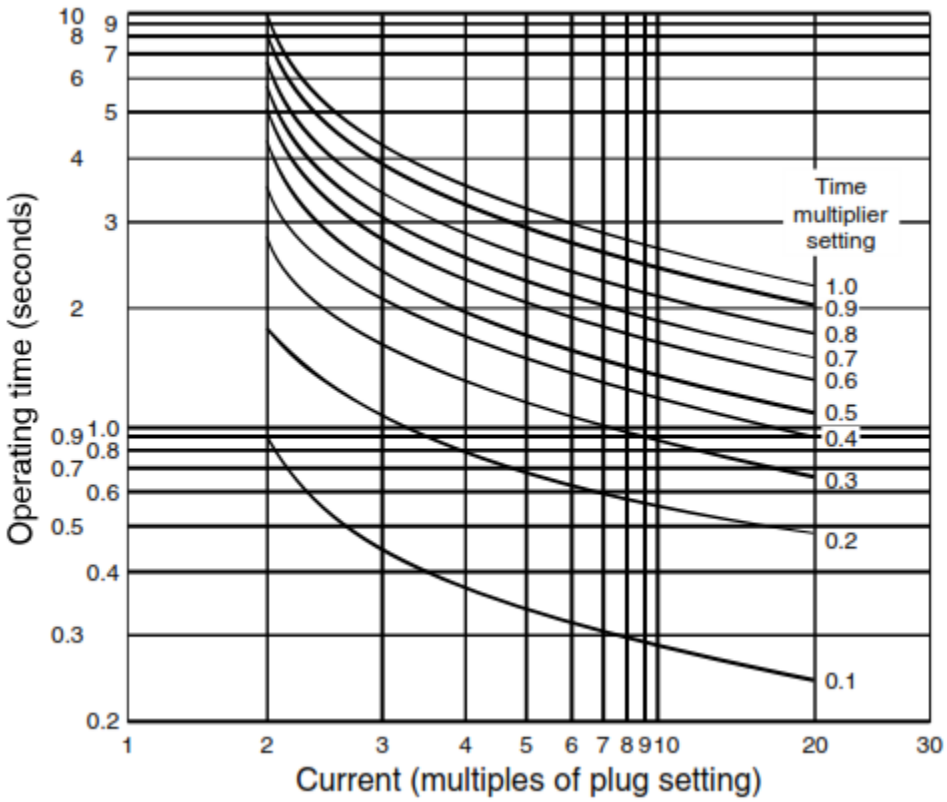



Figure 2 (Figure – 1A given previously)

Answer:

Fault current = 1000 A
CT ratio = 100/5 A

Hence expected current into relay under fault conditions,

$$Ir = (1000 \times 5/100) = 50 \text{ A}$$

Choose plug setting of 5 A (100%). Therefore, current into relay as a multiple of plug setting during fault: 50 / 5 = 10

- We require the relay to operate after 2.4 s as soon as this much current starts flowing in the circuit. Referring to characteristic curves given in Figure 2 above, read time multiplier setting where 10 times plug setting current and 2.4 s cross, which is about 0.8. Accordingly, relay settings = current plug tap 5 A (100%) and time multiplier 0.8.
- Alternatively, if the current plug setting is chosen as 125% (6.25 A), the fault current through the relay will be 50/6.25 = 8 A. The graph shows that eight times plug setting to operate in 2.4 s, the time multiplier should be about 0.7. This technique is fine if the required setting falls exactly on the TM curve. However, if the desired setting falls between the curves, it is not easy to estimate the intermediate setting accurately as the scales of the graph are log/log. The following procedure is therefore recommended (see Figure 3).
- Go to the multiple of plug setting current and read the second value corresponding to the 1.0 time multiplier curve. Then divide the desired time setting by this figure. This will give the exact time multiplier setting:
- Second value at 10 times = 3
- ( at 8 times it is about 3.3s)

  Desired setting = 2.4s.

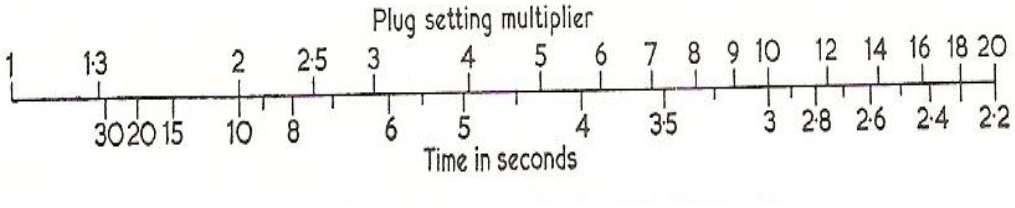



Figure 3
(Figure – 1B previously)

**Logarithmic scale for I.D.M.T. relay**

# Examples :

Example1: Determine the PSM (plug setting multiplier) of a 5A, 2.2 sec over current relay having a plug setting $P_s$=200%. The supply CT is rated 400:5A and the fault current is 12000A.

Solution:

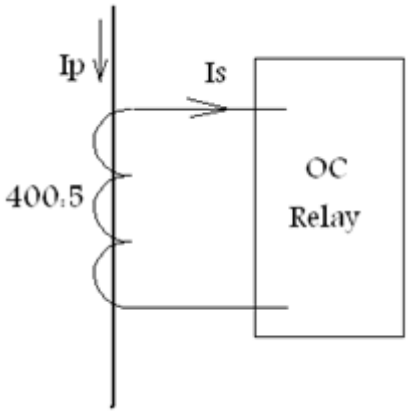
$I_p = 12000A$

$I_s = 12000 \times \frac{5}{400} = 150A$

On PS of 200%:

The relay current $= 5 \times \frac{200}{100} = 10A$

Hence PSM $= \frac{150}{10} = 15$




Example 2: Determine the time of operation of an IDMTL relay rating 5A, 2.2sec and having a plug setting PS= 125% , and TMS=0.6. It is connected to a supply circuit through a C.T of 400/5 ratio. The fault current is 4000A.

Solution:

Since Ps =125% = 1.25

Then the operating current of the relay: 5×1.25=6.25A

$I_p = 4000A$

$I_s = 4000 \times \frac{5}{400} = 50A$

$$PSM = \frac{secondary \cdot current}{relay.operating.current} = \frac{50}{6.25} = 8$$

Now we can find the operating time of the relay in 3 metods :

1) Directly from characteristics of the relay as shown in Fig. EX2-1(if available)

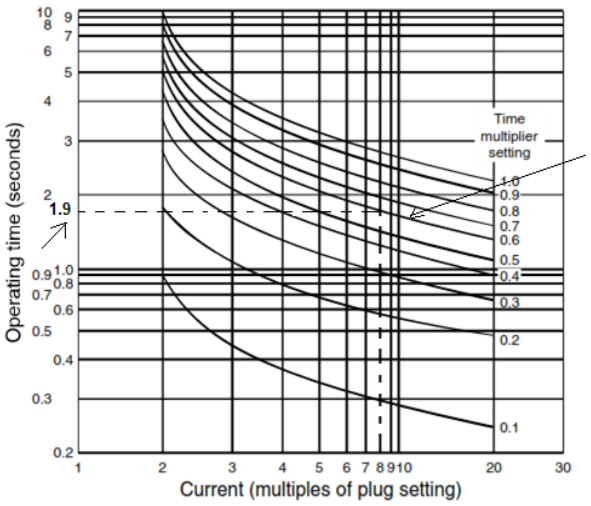



Fig. EX2-1

The operating time of the relay top from figure:
top= 1.9 (approx.)

2) From the curve of TMS=1(Fig. EX.2-2) , the operating time $t_{op}$ for PSM=8 is 3.3sec (TMS=1) and for TMS=0.6 is 1.92sec $(\frac{0.6}{1.0}\times 3.3.)$

This comes from:

| TMS | $t_{op}$ |
|---|---|
| 1 | 3.3 |
| 0.6 | ? |

$?= \frac{0.6}{1.0}\times 3.3.=1.92$ sec

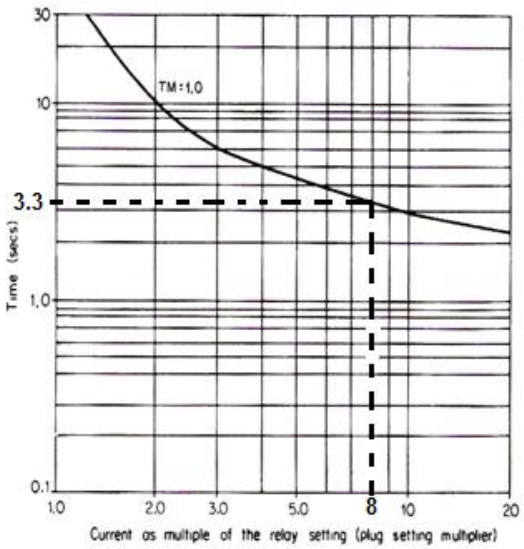



Fig. EX.2-2

3) Or from Fig. EX.2-3

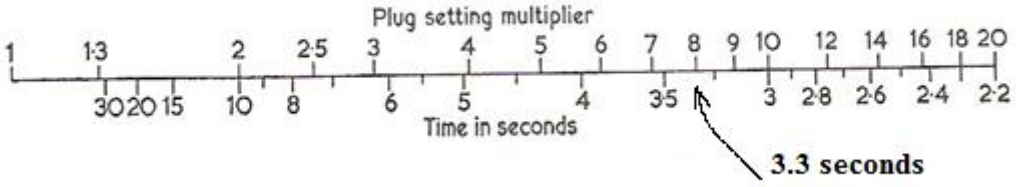



Fig. EX.2-3

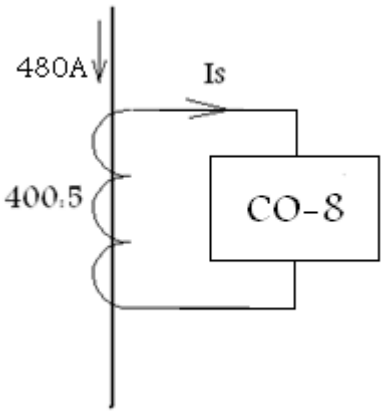
For PSM = 8 , top = 3.3 sec. for TMS =1. Now convert top to TMS =0.6 as above:

| TMS | top |
|---|---|
| 1 | 3.3 |
| 0.6 | ? |

$?= \frac{0.6}{1.0}\times 3.3.=1.92$ sec

Example3: If the rated current (pick up current) of a relay is 3A, and the time dial setting is 1. (a) How long does it take the relay to trip if the supply C.T is rated at 400:5 A, and the fault current is 480A? The type of the OC relay is CO-8.
(b) Solve using the standard curve equation and compare the results.

Solution:




(a) $I_p = 480A$

$$I_s = 480 \times \frac{5}{400} = 6A$$

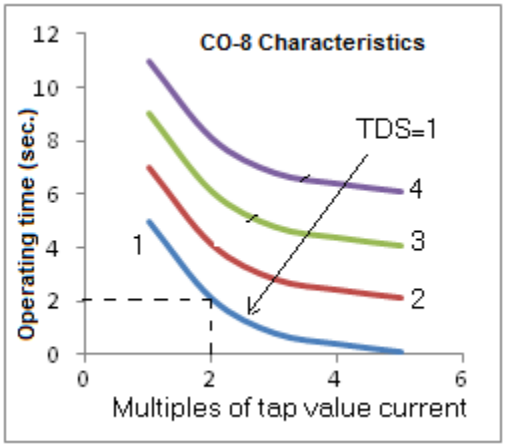
Tap value of current=3A

∴ Multiple of tap value current

$$= \frac{I_s}{I_{tap}} = \frac{6}{3} = 2$$

From the CO-8 characteristic curves (see Figure below) :

Operating time=2.1 sec.




(b) Using the curve equation:

$$t_{relay} = TD\left[\frac{5.95}{M^2 - 1} + 0.18\right]$$

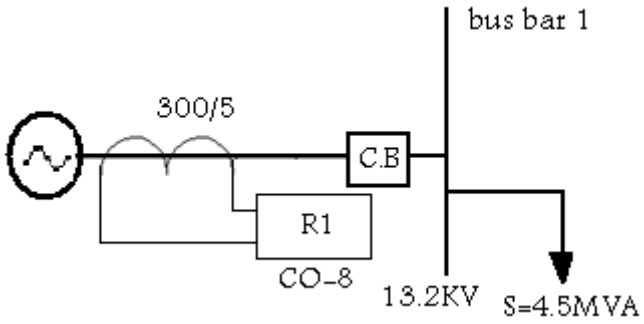
$$TD = 1 \Rightarrow TDS$$

$$M = \frac{I_s}{I_{pickup}} = \frac{I_s}{I_{tap}} = \frac{6}{3} = 2$$

$$\therefore \quad t_{relay} = 1 \times \left[\frac{5.95}{(2)^2 - 1} + 0.18\right]$$

$$= 2.16 \text{sec}$$ (Same result)

Example4: For the relay $R_1$ in the system shown determine the current tap setting CTS. If the maximum three-phase fault current is 2400A and the TDS=2.0 find the operating time if the relay type is CO-8 (inverse type).




Solution:

- Load current at the busbar1

$$I_{L1} = \frac{S}{\sqrt{3}V} = \frac{4.5\times10^6}{\sqrt{3}\times13.2\times10^3} = 196.82A$$

The relay current $I_R = 196.82\times\frac{5}{300} = 3.28A$

Since the current tap setting (CTS) of CO-8 relay available are 4,5,6,7,8,10 and 12

Hence we choose CTS=4

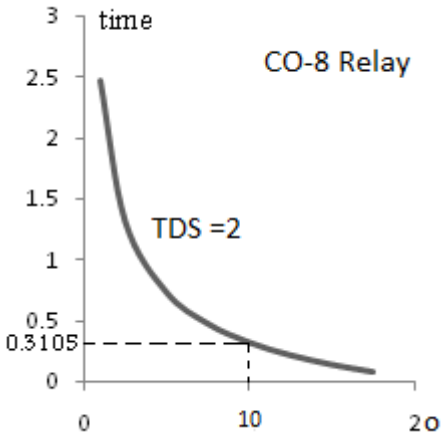
- Fault current $I_f = 2400A$

$\therefore$ Relay current during fault $= 2400\times\frac{5}{300} = 40A$

As multiple of selected CTS $= \frac{40}{4} = 10$

From the CO-8 ch/s curve:

Operating time $\cong 0.3105\text{sec}$



# Power system protection Notes

# Transmission and distribution lines protection

Dr.Professor Mohammed Tawfeeq Al-Zuhairi

# Transmission and distribution lines protection

- Transmission lines are exposed to short circuits between phases or from phase to ground. The range of the possible fault current, the effect of load, the question of directionality and the impact of system configuration are all part of the transmission line protection problem.

- **Line Classification**
  - Distribution: 33 kV and lower
  - Subtransmission: 33 – 132 kV
  - Transmission: 132 kV and higher
  - HV : 132 – 220 kV
  - EHV: 400 – 750 kV
  - UHV: 1000 kV and higher

## Transmission Line Protection Principles

We use four protection principles for distribution and transmission lines.

- Overcurrent (instantaneous overcurrent and inverse, time delay, overcurrent ) (50, 51, 50N, 51N)
- Directional Overcurrent (67, 67N)
- Distance (21, 21N)
- Differential ( pilot) (87)

-Overcurrent protection, the simplest and most economical of these principles, is limited to radial lines. Overcurrent protection has found widespread use in distribution utility and industrial systems.
-The addition of directionality extends the application of overcurrent protection to looped lines.
-We use distance protection in many transmission lines. In order to increase operating speed.
we may use a communications channel to exchange information between directional or distance elements. This type of arrangement is directional comparison pilot protection.
Finally, we may apply the differential principle to transmission lines over a communications channel. This arrangement offers the best protection.

# 1.Overcurrent protection of transmission and distribution lines

Overcurrent protection is the simplest and most economical of TL protection schemes .It is limited to radial lines.

- Protection of Radial System by Overcurrent Relay:

Consider a case of a radial line supplying three substation as shown in Fig.1:

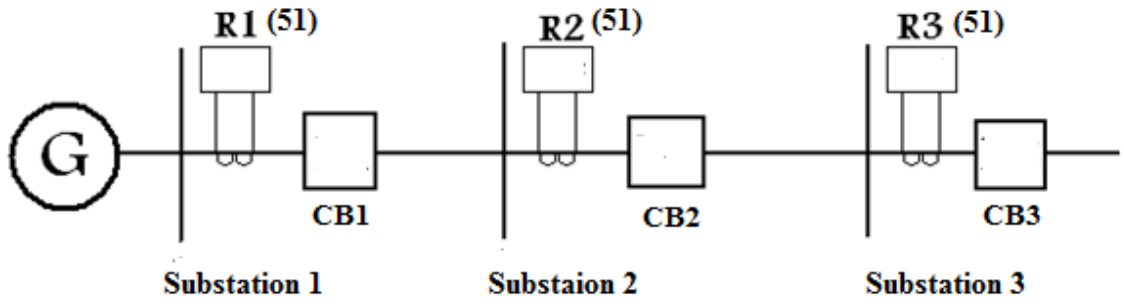



Fig.1

The protection scheme must satisfy the following requirements:

a) Under normal conditions the breakers are not tripped.

b) Under fault conditions only the breakers closest to the fault on the source side are tripped.

c) If the closest breaker fails to operate, the next breaker closer to the source should trip.

Hence, the relay operations must be coordinated with respect to each other in order to provide the desired selectivity. This is called “relay coordination”.

Among the various possible methods used to achieve correct relay coordination are those using either time or current, or a combination of both. The common aim of all three methods is to give correct discrimination. That is to say, each one must isolate only the faulty section of the power system network, leaving the rest of the system undisturbed.

There are three methods for obtaining relay coordination

- Discrimination by time (Time-grading).
- Discrimination by current (Current-grading).
- Discrimination by both time and current (Time-Current grading)

❖ **Time-grading (Discrimination by time)**

In this method, an appropriate time setting is given to each of the relays controlling the circuit breakers in a power system to ensure that the breaker nearest to the fault opens first.

overcurrent relay with definite time characteristic are used. The relay characteristic is shown in Fig.2

For the system shown in Fig.1.

$R_3$ → 0.25 sec.

$R_2$ → 0.50 sec.

$R_1$ → 1.0 sec.

The relay settings are shown graphically in Figs.2 (b) and (c).

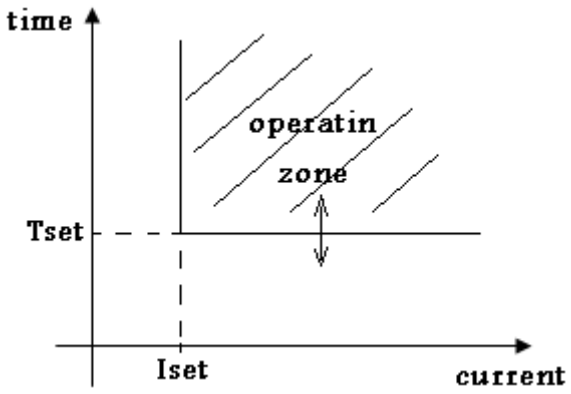



Fig 1(a): Definite-time characteristic

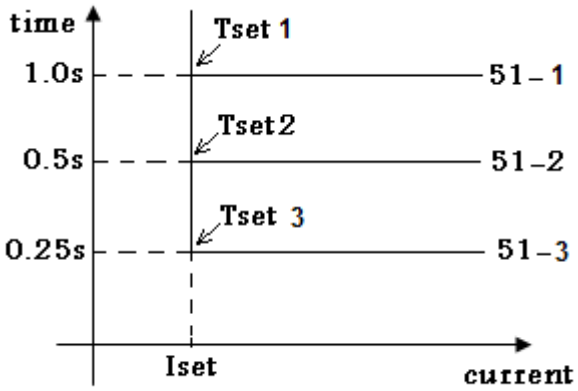



Fig 2(b) relay

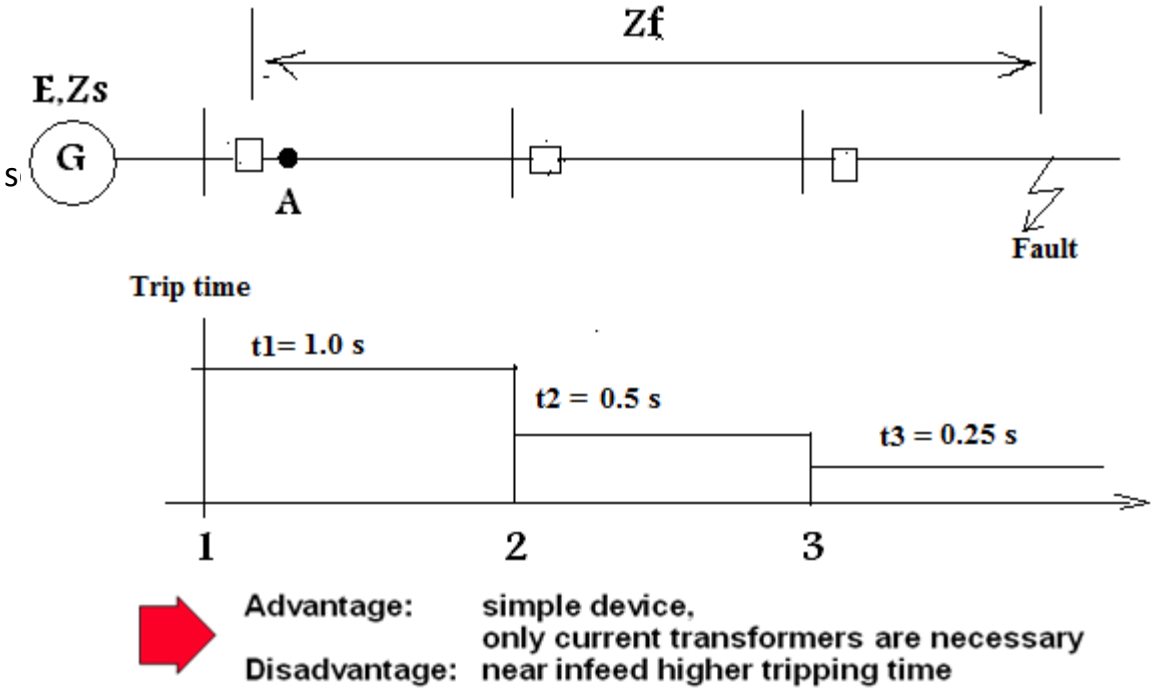
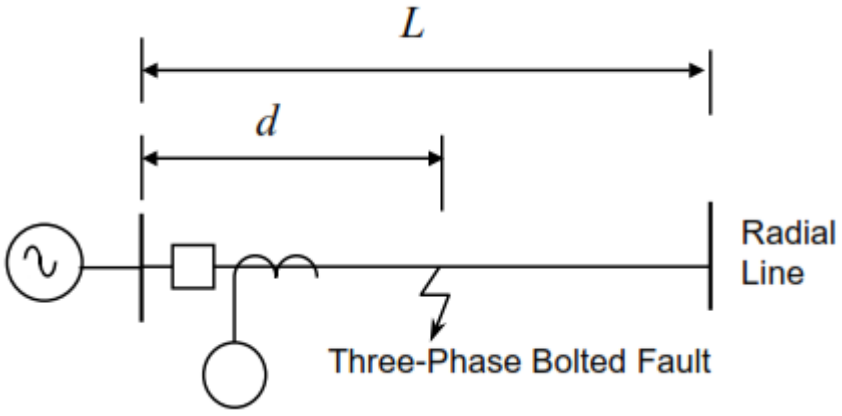



Fig 2(c)

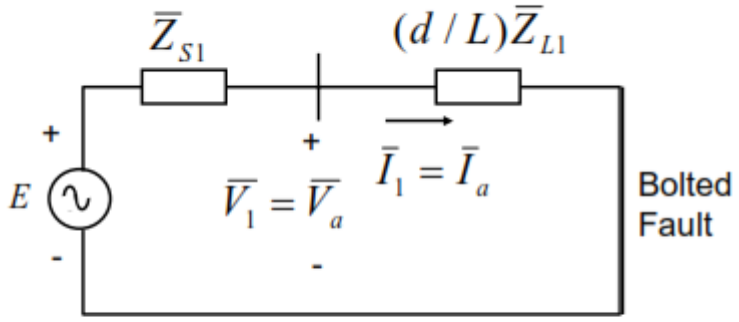
The disadvantage of this method is that in case of occurrence of fault near the source (point A for example) a large current will be produced and is very destructive if not remove quickly. This means that the heaviest faults are cleared slowly.
The fault current can be calculated as:

## Three-Phase Fault on a Radial Line




For a perfect three-phase fault, only the positive-sequence impedance is involved in the calculations. With the usual convention, the phase “a” voltage and current are equal to the positive-sequence voltage and current.

## Impedance Diagram




$$\bar{I}_1 = \bar{I}_a = \bar{I}_{FAULT} = \frac{E}{\bar{Z}_{S1} + (d/L)\bar{Z}_{L1}}$$

- *Zs1* is System's Thevenin Equivalent Impedance.
- It Depends on Whole System State (Topology, Load, etc.).

The positive-sequence impedance diagram for a three-phase fault is as shown in the figure above.For this radial system, disregarding the influence of load, the fault current in each phase is balanced and is equal to the phase current measured by the relays at the substation.This current depends on the following parameters:
• System voltage
• Line impedance
• Distance to the fault
• Thevenin impedance equivalent to the system "behind" the substation bus
The Thevenin impedance depends on the conditions of the system, such as the topology and system loading.

❖ Discrimination by current (Current-grading).This method is used only in LV systems due to its disadvantages in HV systems.

Discrimination by current relies on the fact that the fault current varies with the position of the fault because of the difference in impedance values between the source and the fault. Hence, typically, the relays controlling the various circuit breakers are set to operate at suitably tapered values of current such that only the relay nearest to the fault trips its breaker.

❖ **Discrimination by both time and current (Time-Current grading) using Inverse, time-delay overcurrent relays**

- In the time – current grading method, the time – current grading is achieved with the help of relays that have inverse time – overcurrent characteristics
- Two settings for each relay are required: CTS and TDS (or PS and TMS).
- Fig.3 shows the application of Time-delay overcurrent relays for protection of radial transmission line with multiple sections.It illustrates how time coordination is achieved between the inverse time – overcurrent relays at each breaker location.

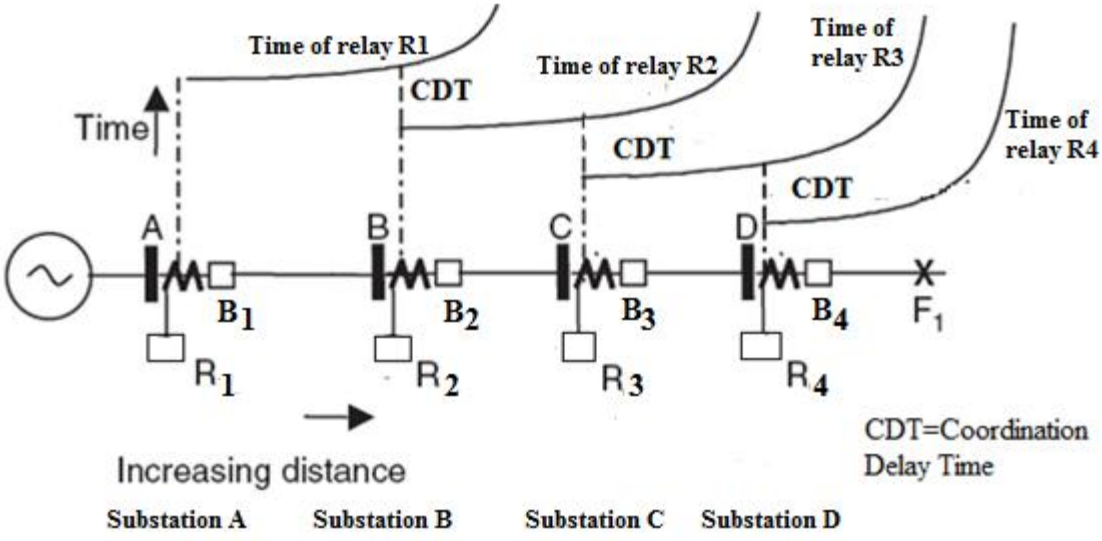



Fig.3 Relay coordination principle.

- The coordination between the relays for fault at F1 is necessary. The relay R4 tripping breaker B4 operates quickly at time T1, followed by the relays controlling B3, B2 and B1 so that B4 operates before B3, B3 before B2 and B2 before B1.
  Therefore the operating time T2 of relay R3 can be expressed as

$$T2 = T1 + CDT$$

  where CDT is called the coordination delay time (CDT), which is the minimum interval that permits a relay and its circuit breaker to clear a fault in its operating zone.

## 1. American school of coordination:

In American standard, the time interval between two adjacent relays is called the coordination delay time (CDT). The value of CDT is 0.4 seconds. This comes from:

- Fault current interruption time of the circuit breaker (= 0.1 s, or 6 cycles in 60 Hz system).
- Error margin of 0.3 s .
  Hence,
  CDT=(operating time of breaker B4) + (error margin)
  Similarly, the operating times of R2 and R1 are:
  T3=T2 + CDT
  T4=T3+ CDT

### CTS and TDS Settings

The current tap setting CTS and time dial setting TDS are found according to the following strategies which come from experience:

$$CTS \leq \frac{1}{3} \times \text{Minimum fault current}$$
$$CTS \geq 2 \times \text{Maximum load current}$$

TDS is selected so that there is at least a 0.4 s as coordination time delay (CDT).

## 2. IEC and British school of coordination:

Same as American school but taking CDT = 0.5 s as coordination delay time between two adjacent relays.

## Example 1

For the 13.8 kV feeding system shown in Fig.1, determine satisfactory relay settings .
Pertinent system data is provided in Table1.Assume three relays per breaker, one for each phase ,Fig.2. Consider only 3-phase faults with short circuit MVA = 10. Use the overcurrent relay whose characteristic is given in Fig.3.

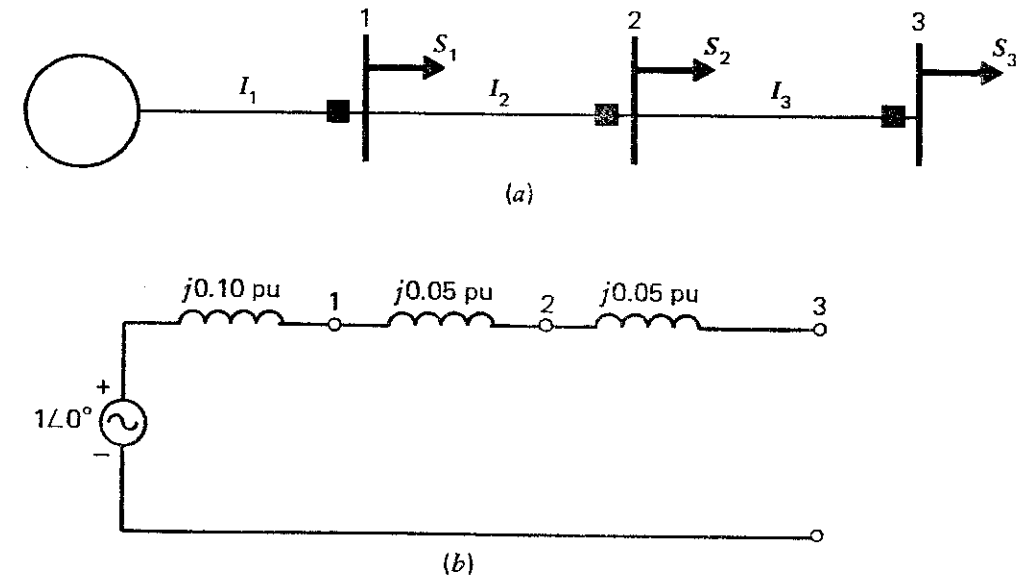



**Fig.1**

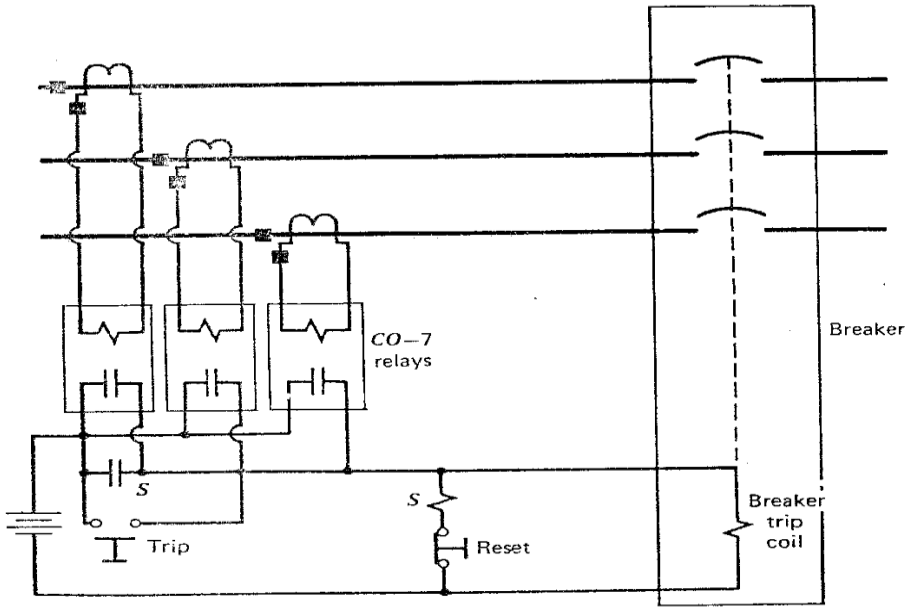



Fig.2

Table 1.

| Bus | S in MVA | P.F (lag) | Breaker | CT ratio |
|---|---|---|---|---|
| 1 | 8.5 | 0.8 | B1 | 800/5 |
| 2 | 3 | 0.8 | B2 | 400/5 |
| 3 | 5 | 0.8 | B3 | 400/5 |

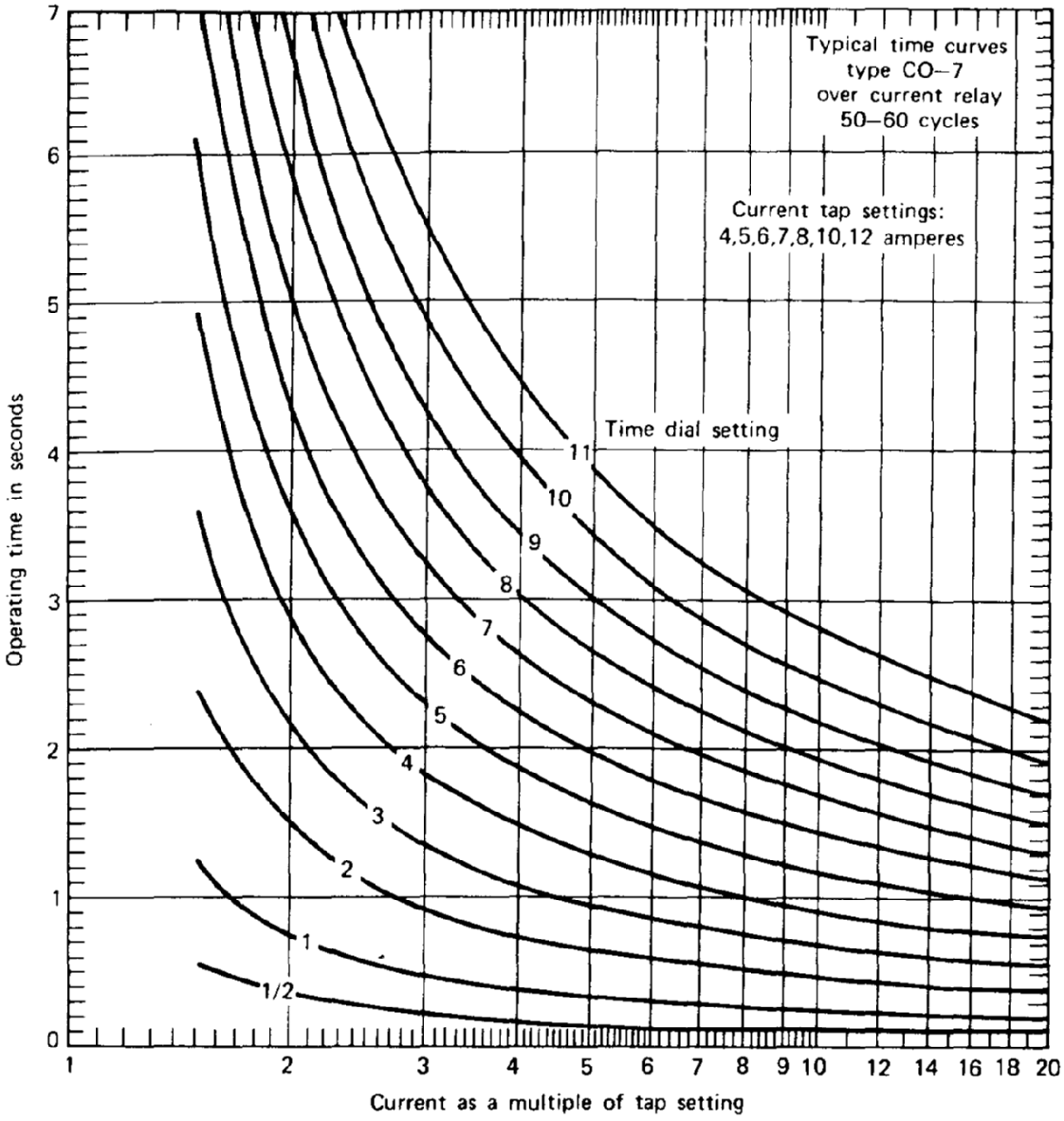



Fig.3

Solution

Observe that relays are all *CO*-7s, whose characteristics are provided in Figure 3. Two settings are to be determined for each triad of relays; the CTS and the TDS. We start with *B*3.

Considering load,

$$I_3 = \frac{5}{0.0138\sqrt{3}}$$

$$= 209 \text{ A}$$

$$I_{3_{relay}} = \frac{209}{400/5}$$

$$= 2.61 \text{ A}$$

Considering a fault at bus 3,

$$I_3 = \frac{1}{0.2} = 5.0 \text{ pu}$$

$$= 5\left(\frac{10}{0.0138\sqrt{3}}\right) = 2092 \text{ A}$$

$$I_{3_{relay}} = \frac{2092}{400/5}$$

$$= 26.1 \text{ A}$$

Thus,

$$2 \times 2.61 \leq \text{CTS}_3 \leq \frac{1}{3} \times 26.1$$

$$5.22 \leq \text{CTS}_3 \leq 8.70$$

$$\therefore \quad \text{select CTS}_3 = 6 \text{ A}$$

Also, select $\text{TDS}_3 = \frac{1}{2}$ (fast as possible)

Now the multiple of current tap setting m is;

$$m_3 = \frac{I_{relay\,3}}{CTS3} = \frac{26.1}{6} = 4.35$$

From relay characteristics, the operating time of relay -1 is $t_{op1}$=0.18 s.

Now, consider settings for *B*2.

Considering load,

$$I_2 = \frac{8}{0.0138\sqrt{3}}$$

$$= 335 \text{ A}$$

$$I_{2_{relay}} = \frac{335}{400/5}$$

$$= 4.18 \text{ A}$$

$$8.36 \leq \text{CTS}_2 \leq 11.6 \text{ A}$$

$$\therefore \quad \text{Select CTS}_2 = 10 \text{ A}$$

Considering a fault at bus 2,

$$I_2 = \frac{1}{0.15} = 6.67 \text{ pu}$$

$$= 2789 \text{ A}$$

$$I_{2_{relay}} = \frac{2789}{400/5}$$

$$= 34.9 \text{ A}$$

To determine $TDS_2$, consider a fault at bus 3. The desired operating time for relay 2 is

$$t_{op2} = t_{op3} + CDT$$
$$= 0.18 + 0.4 = 0.58s$$

$$m_2 = \frac{I_{2_{relay}}}{CTS_2} = \frac{26.1}{10} = 2.61$$

$\therefore$ select $TDS_2 = 1.1$ From the characteristics of the relay.

For fault near relay-2 :

$$m_2' = \frac{I_{2relay}'}{CTS2} = \frac{34.9}{10} = 3.49$$

From the relay characteristics again
For TDS2 =1.1 and $m_2'$ = 3.49 , the new operating time of relay2 must be = 0.45s.
Now consider setting of B1 :

Considering load,

$$I_1 = \frac{16.5}{0.0138\sqrt{3}}$$
$$= 690 \text{ A}$$
$$I_{1_{relay}} = \frac{690}{800/5}$$
$$= 4.31 \text{ A}$$

Considering a fault at bus 1,

$$I_1 = \frac{1}{0.1} = 10 \text{ pu}$$
$$= 4184 \text{ A}$$
$$I_{1_{relay}} = \frac{4184}{800/5}$$
$$= 26.1 \text{ A}$$

$$8.62 \le CTS_1 \le 8.72$$

Select $CTS_1 = 8$ A, which cheats a little on the lower bound but is the best we can do.

To determine, $TDS_1$, consider a fault at bus 2. The desired operating time for relay 1 is:

Relay 2 operating time 0.45 s

Relay 1 operating time = 0.45 +04 = 0.85 s

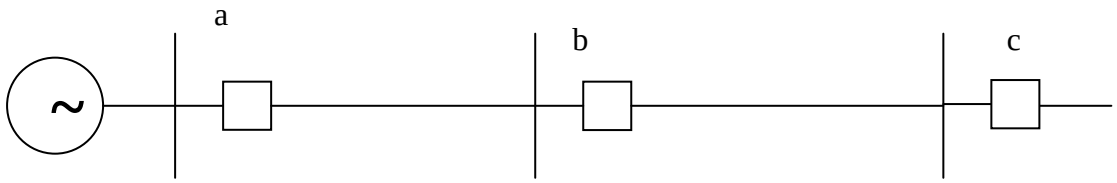
To find $TDS_1$ : For fault at relay 2

$$\frac{I_{1_{relay}}}{CTS_1} = \frac{2789(5/800)}{8} = 2.18$$

$\therefore$ $TDS_1 = 1.3$

## Example 2 on IEC school of coordination:

It is required to provide time-current grading for the following system:




| *Relay point* | *Plug setting(PS)* | *CT ratio* | *Fault current* |
|---|---|---|---|
| a | 125% | 400/5 | 6000A |
| b | 125% | 200/5 | 5000A |
| c | 100% | 200/5 | 4000A |

Use 2.2 sec. IDMTL characteristic for time multiplier setting (TMS) = 1 according to British Standard given in the following figure1:

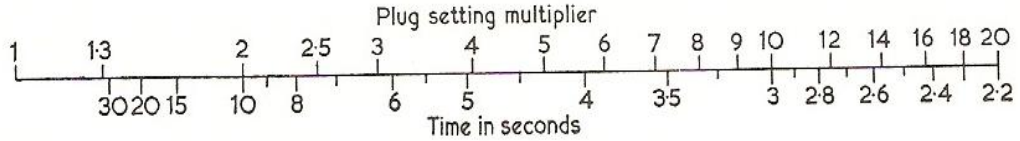
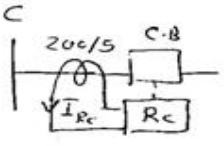



Figure1

***Solution :***

- At relaying point C, the relay current on fault:

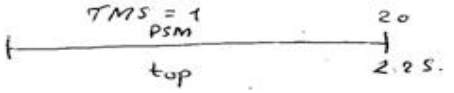
$$I_{Rc} = 4000 \times \frac{5}{200} = 100\ A.$$




For PS = 100%

$$PSM = \frac{100}{5 \times 1} = 20$$

For TMS = 1.0 curve, the operating time correspond to PSM = 20 is 2.2 S




If we select $R_C$ to operate with fastest time, hence TMS = 0.1, thus the operating time for $R_C$ will be:

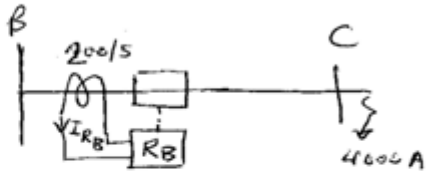
$$top\Big|_{Rc} = \frac{0.1 \times 2.2}{1.0} = 0.22\ sec.$$

Hence For Relay C: **TMS = 0.1** & **top = 0.22 Sec**

- For relay at B :

This relay should respond to fault at C (backup) and respond to fault near B :

– Fault at C :




For discrimination between $R_C$ & $R_B$, let the time margin = 0.5 Sec.

Hence $top|_{R_B} = 0.22 + 0.5 = 0.72$ Sec.

For fault at C

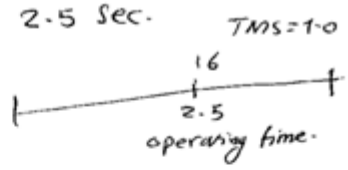
$$I_{R_B} = \frac{4000}{\frac{200}{5}} = 100 \text{ Amps.}$$

The PS of relay B = 125%,

hence the operating current = $5 \times 1.25 = 6.25$ A.

$$\therefore \text{PSM} = \frac{100}{6.25} = 16.$$

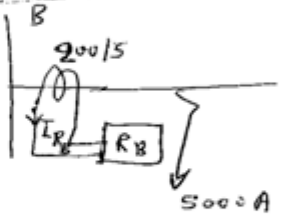
From curve, the operating time is 2.5 Sec.




The operating time of $R_B$ when graded with $R_C$ is 0.72 Sec.

hence $TMS = \frac{0.72}{2.5} = 0.29$.

| TMS | top |
|---|---|
| 1 | 2.5 |
| x | 0.72 |

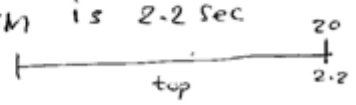



– For fault near B :

$$I_{R_B} = 5000 \times \frac{5}{200} = \frac{5000}{40}$$

$$\therefore \text{PSM} = \frac{5000}{6.25 \times 40} = 20$$

The operating time correspond to this PSM is 2.2 Sec




$\therefore$ Actual operating time of $R_B$ is

$$top|_{R_B} = 2.2 \times \left(\frac{TMS=0.29}{TMS=1.0}\right) = 0.638 \text{ Sec.}$$

| | |
|---|---|
| top | 0.638 sec |
| TMS | 0.29 |

**Relay B settings**

### 3. Instantaneous overcurrent relays (50)

In order to properly apply the instantaneous overcurrent relay there must be a substantial reduction of short-circuit current as the fault is moved away from the relay toward the far end of the line. The relay must be set not to overreach the bus at the remote end of the line and there still must be enough of a difference in the fault of a difference in the fault current between the near and far end faults to allow a setting for the near-end fault.
This will prevent the relay from operating for faults beyond the end of the line and, at the same time, will provide high-speed protection for an appreciable portion of the circuit.

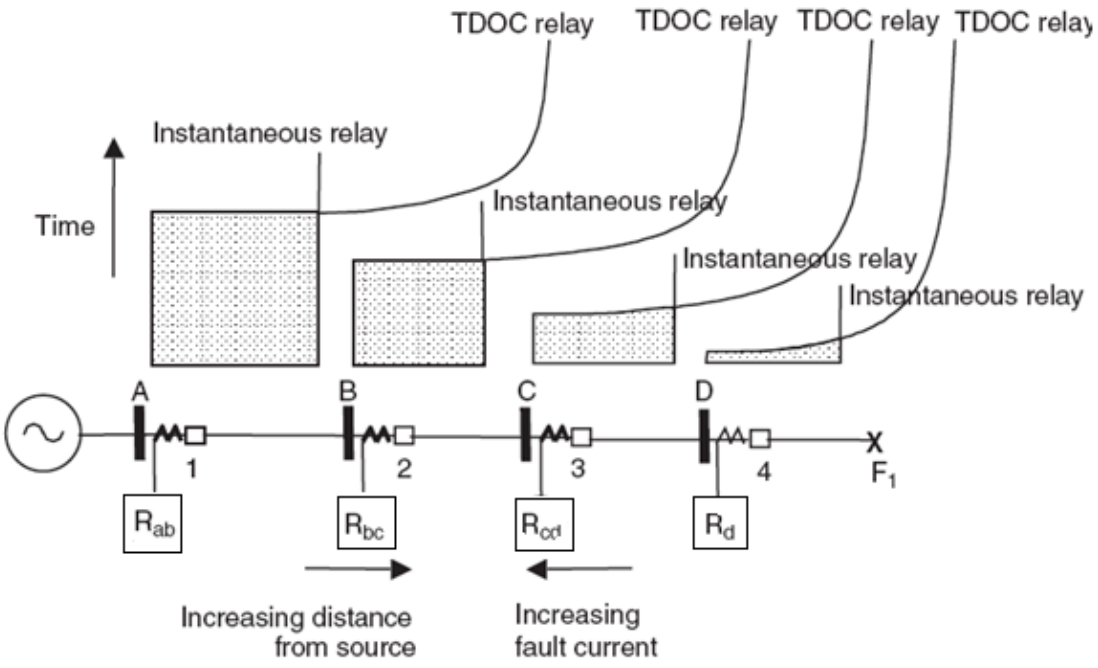
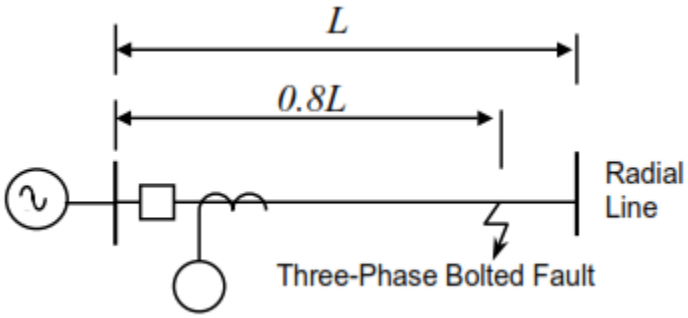



Fig.5 Application of instantaneous relay (TDOC =time delay overcurrent ).

## Overcurrent Relay Setting and Reach

Since the instantaneous relay must not see beyond its own line section, the values for which it must operate are very much higher than even emergency loads. Therefore, load is not usually a consideration for the instantaneous relay setting.

- Phase Instantaneous Element (50) Commonly Set to Reach Faults up to 80% of Total Line Length




- Relay Setting Calculated for a Given Value of $Z_{S1}$

$$I_{SETTING} \approx \left| \frac{E}{\overline{Z}_{S1} + (0.8)\overline{Z}_{L1}} \right|$$

A phase instantaneous overcurrent element is set to detect fault currents up to 80 percent of the line length. This gives enough security margin (20 percent) to avoid non-selective operation for faults beyond the remote bus. The relay setting is calculated for a given value of the equivalent $Z_{S1}$.

# 4. Directional overcurrent relays

| Power system protection | Dr.Mohammed Tawfeeq |
|---|---|
| Ring system Protection using directional relays | |

## Directional Relays

The radial lines (feeders) and its protection devices are usually simple and inexpensive. But if a fault occurs on a radial line all consumers behind the fault will loose their supplies.
When systems become complex, time delay coordination of overcurrent relays becomes quite complicated and in some cases impossible. To understand the problem, consider the system shown in Figure 1. Suppose there is a fault at point X. Breakers B3 1 and B32 will sense the same currents. We want B31 and B13 to operate to clear the fault. (If B32 operates, we lose service at bus 3.) By using time delay overcurrent relays, we can set B31 faster than B32. However, let us now consider a fault at point Y. Breaker B31 will trip before B32, isolating bus 3 (after B23 trips). It is therefore impossible to coordinate time delay overcurrent relays so that line faults do not result in the loss of a bus in this system.
This problem can be overcome by using the directional relay Shown in Fig 2.

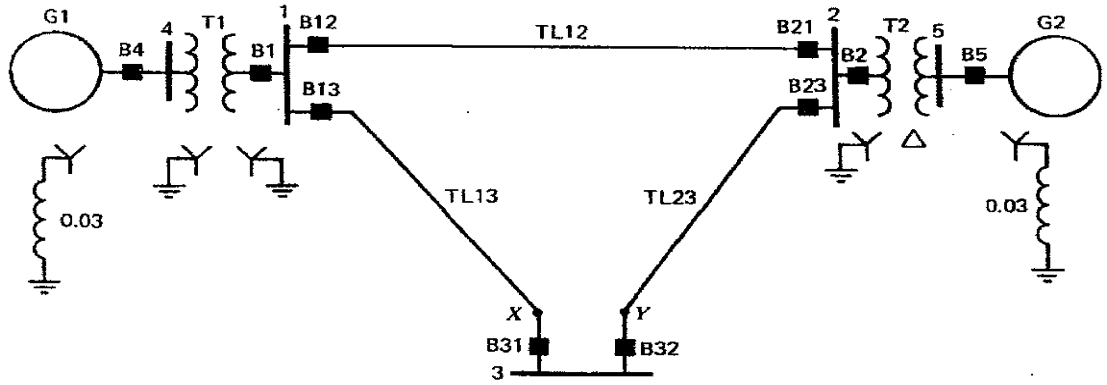



Fig-1

- The directional relay is only operates when its fault is inside its protection zone
- Directional relays are usually of the wattmetric induction type.
- The six breakers B12,B21,B13, B31,B23,B32 should be controlled by directional relays arranged to respond to faults on the line side of the breaker.
- Directional relay is blind for fault behind it. It looks forward only.
- When overcurrent relay is used with directional relay , there contacts should be connected in series as shown in Fig.2

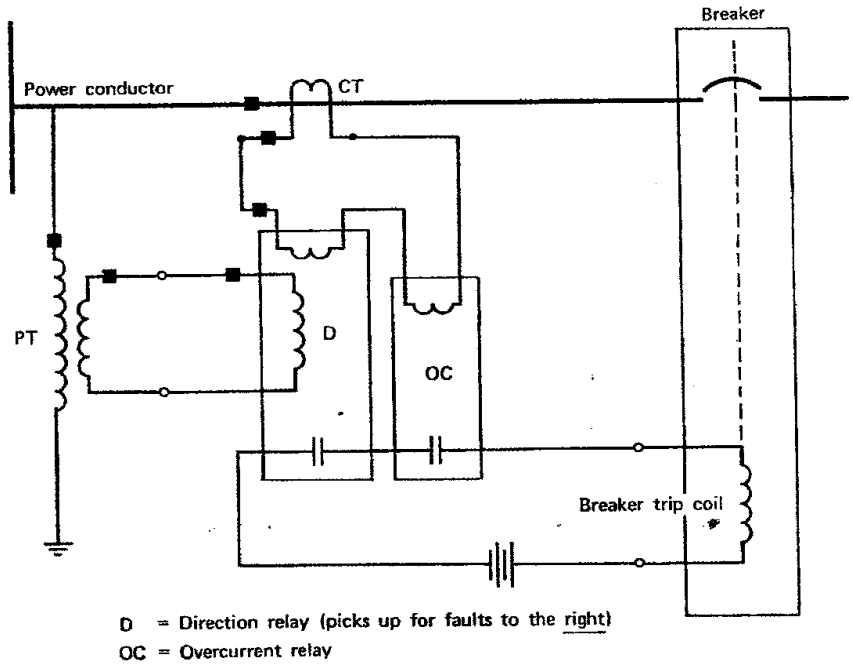



Fig.2 Basic arrangement for applying of directional relay .One phase shown.

# Differential Protection

# (Unit protection)

# Differential Protection

- Differential protection is the best technique in protection. In this type of protection the electrical quantities entering and leaving the protected zone or area are compared by current transformers (C.T.s). If the net difference equal zero, it means no fault exist.
- This system is operating in either of the two following principles:
  1. **Current balance principle.**
  2. **Voltage balance principle.**
- Differential protection is applicable to all parts of the power system:
  1. Generator.
  2. Transformers.
  3. Motors.
  4. Buses.
  5. Lines and feeders.
  6. Reactors and capacitors

  There are two basic types of differential protection:
    - Current Balance Differential protection
    - Voltage Balanced Differential Protection

**1. <u>Current Balance Differential protection:</u>**

➢ <u>Operation during internal and external fault conditions</u>

Fig.1 shows the basic current differential protection based on current balance principle.

- At ***normal conditions and for external fault at F,*** $CT_1$ and $CT_2$ circulate currents at their secondary's $I_{s1}$ and $I_{s2}$ ($I_{s1} = I_{s2}$) and no current flow through the relay ($\Delta I = I_{s1} - I_{s2} = 0$), hence the relay will not operate.
- If fault occurs at point ***F*** within the protected zone (***internal fault***) as shown in Fig.2, and the fault is fed from both sides, then current through $C.T_2$ will be reversed. Therefore a current $\Delta I = I_{s1} + I_{s2}$ will flow in the operating winding of the relay. This will cause the relay to trip the circuit breaker connected to the faulty system. Hence the relay trips when

  $| I_{s1} + I_{s2}| > |I|$ $|I|$=> pick up current of relay

  <u>This form of protection is known as Merz-Price protection.</u>

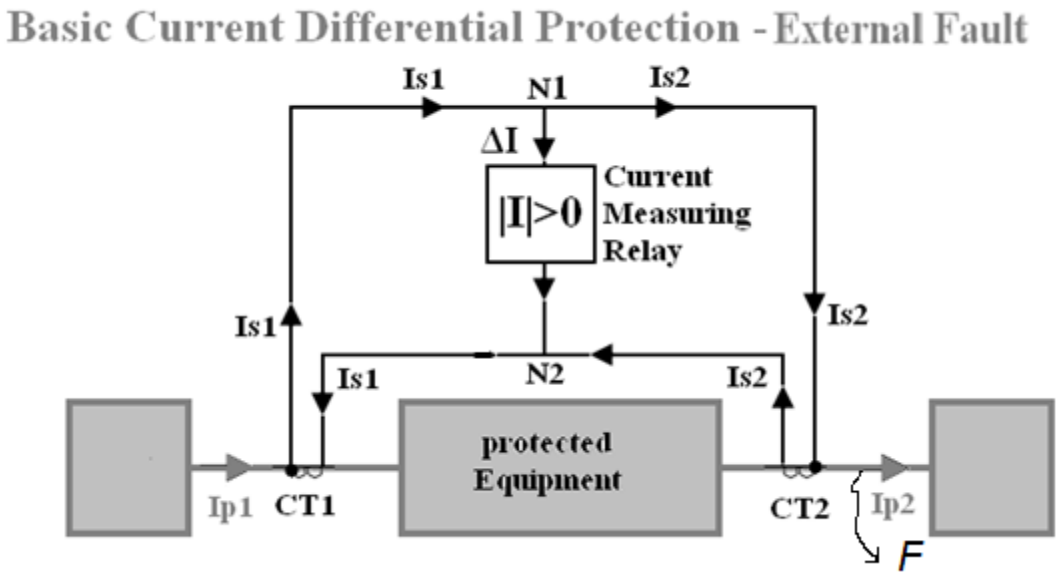



**Fig 1**

Consider ideal current transformer performance

- $I_{p1} = I_{p2}$
- Therefore $I_{s1} = I_{s2}$
- Therefore $\Delta I = 0$, magnitude of $I = 0$
- Current measuring relay does not operate.

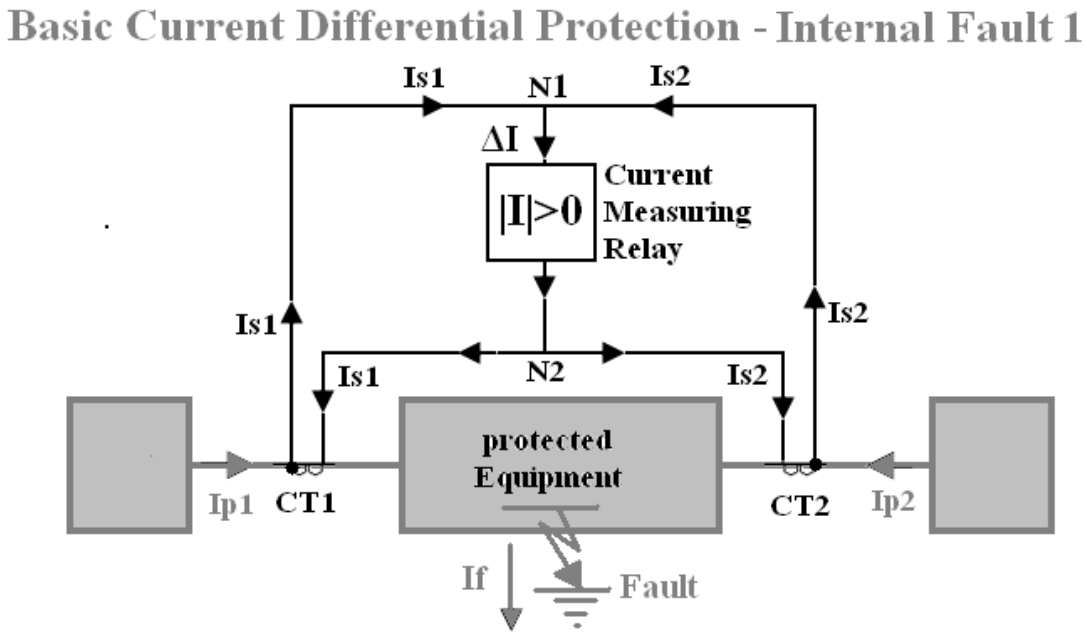



**Fig. 2 internal fault with two infeed.**

Consider ideal current transformer performance

- $I_f = I_{p1}+I_{p2}$
- Therefore $I_{s1} \neq I_{s2}$
- Therefore $\Delta I = I_{s1}+I_{s2} \neq 0$, magnitude of $I > 0$
- Current measuring relay operates.

-Relay may also operate if the fault in feed is from one direction as shown in fig.3.

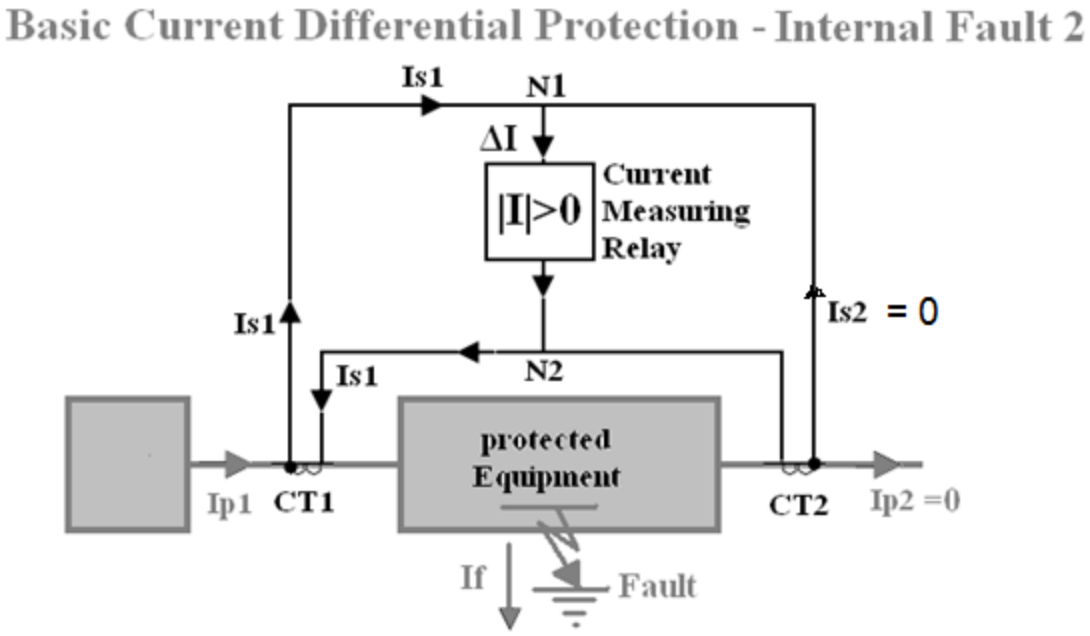



**Fig 3 internal fault with one infeed.**

Consider ideal current transformer performance:

- $I_f = I_{p1}$ as $I_{p2} = 0$ i.e no fault current in feed from one side.
- $I_{s2} = 0$
- Therefore $\Delta I = I_{s1} \neq 0$, magnitude of $I > 0$
- Current measuring relay operates.

**2. <u>Voltage Balanced Differential Protection</u>**

Instead of current balance, a voltage balance Mertz-Price system, shown in Fig.4, is used for feeder protection or equipment protection (unit protection).

- $CT_1$ & $CT_2$ secondary windings are connected in opposition so that there is no current flow in the relay operating coil ($V_{s1} = V_{s2}$ => relay not operate).
  - During internal fault $V_{s1} - V_{s2} \neq 0$, this will drive current through the operating coil of the relay and the relay will operate.Fig.5.

## Balanced Voltage Differential Protection - External Fault

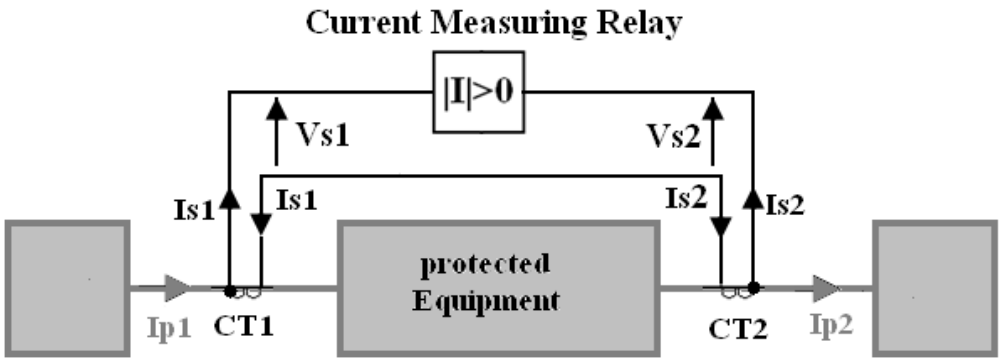



**Fig 4**

Consider ideal current transformer performance:

- $I_{p1} = I_{p2}$.
- $V_{s1} = V_{s2}$ and $I_{s1} = I_{s2} = 0$.
- Therefore magnitude of I = 0
- Current measuring relay does not operate.

## Balanced Voltage Differential Protection -Internal Fault

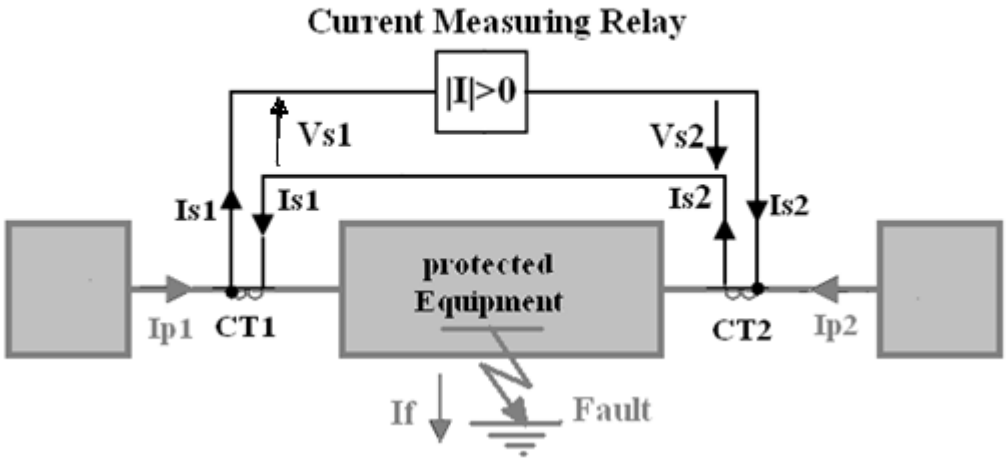



**Fig 5.**

Consider ideal current transformer performance:

- $V_{s1} \neq V_{s2}$.
- Therefore magnitude of $I \neq 0$
- Current measuring relay operates.

➢ The characteristics of **differential protection** can be summarized as follows:

Simple Concept:

• Measure current entering and exiting the zone of protection

• If currents are not equal, a fault is present

Provides:

• High sensitivity

• High selectivity

Result:

• Relatively high speed

## ➢ Percentage Differential Current Relay

This relay has an operating winding and two restraining winding connected as shown in Fig.6. The function of the restraining windings is to prevent undesired relay operation should a current flow in the operating winding due to CT during external fault.

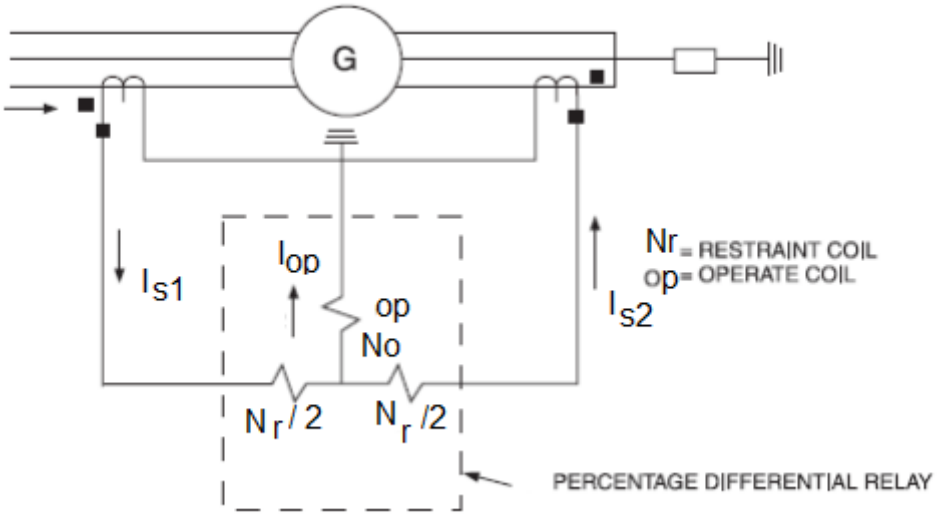



Figure 6—Basic relay connections (one phase) for fixed percentage restraint differential relay.

At Normal conditions:

- The differential current in the operating coil is proportional to $Is_1$-$Is_2$.
  $\therefore \quad I_{op} = Is_1 - Is_2$
- The equivalent current in the restrain windings are proportional to ½ ( $Is_1$+$Is_2$) since the two restrain windings are identical.
  $\therefore \quad I_{rest} = ½ ( Is_1 + Is_2)$

- Therefore, the ratio of the differential operational current to the average restrain current is a fixed "percentage". In other word, we can define the **bias** as the ratio between the numbers of turns of the restrain coil to the number of turns of the operating coil, i.e.

$$\%bias = \frac{N_r}{N_o} = k$$

- k is typically (10 – 40%).

- The operating characteristics of the relay is shown in Fig.7

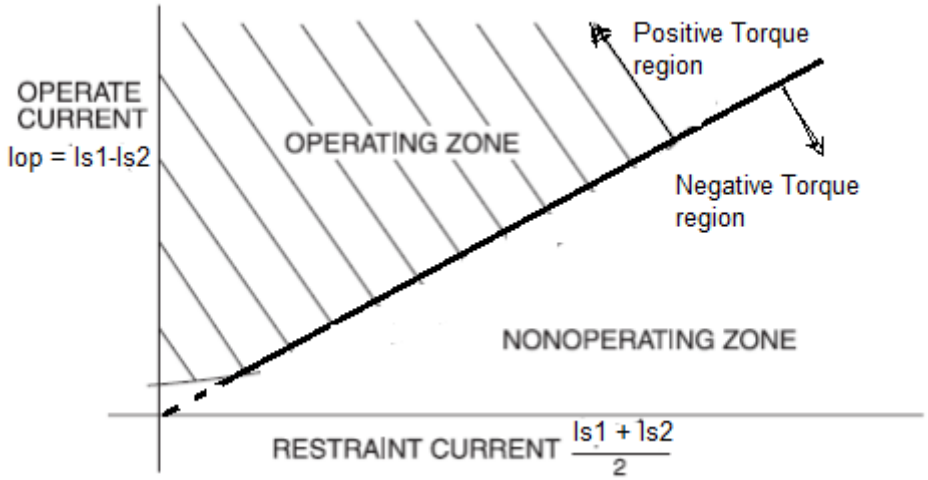



Fig. 7 Typical operating characteristic of a percentage differential relay.

The electromagnetic forces are proportional to the square of the magneto-motive force (mmf).
The condition for relay operation is then:

$$(mmf_{op})^2 > (mmf_r)^2$$

$$(I_{s1}-I_{s2})\, N_o > ½ (I_{s1}+I_{s2})\, N_r$$
$$(I_{s1}-I_{s2})\, N_o > ½ (I_{s1}+I_{s2})\, k\, N_o$$

$$I_{s1} > (½ ( I_{s1}+I_{s2})) k + I_{s2}$$

$$I_{s1} – ( k /2) I_{s1} > ( ½ I_{s2}) k + I_{s2}$$

$$I_{s1} (1 –½ k) > I_{s2} (1+ ½ k)$$

$$I_{s1} > \frac{(1 + ½ k)}{(1 – ½ k)} I_{s2}$$

$$I_{s1} > \frac{(2 + k)}{(2 – k)} I_{s2}$$

These characteristics can be achieved using balanced beam relay shown in Fig.8.

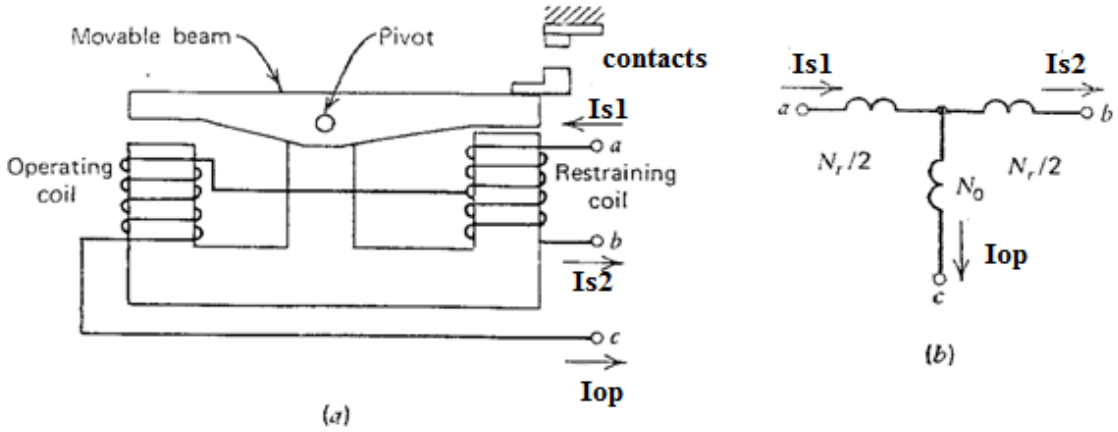



Fig.8 Balanced beam relay with restrain . (a) Balanced beam type relay (b) Schematic

Example: A balanced-beam relay has a pick up current of 0.1 A and a 10% slop. If the restrain coil currents are $I_{S1} = 4.2$ A and $I_{S2} = 4$ A, would the relay operate?

Solution:

$I_{S1} = 4.2$ A

$I_{S2} = 4$ A.

The restrain coil has average current of

$$I_{rest} = \frac{I_{S1} + I_{S2}}{2} = \frac{4.2+4}{2} = 4.1 \text{ A}.$$

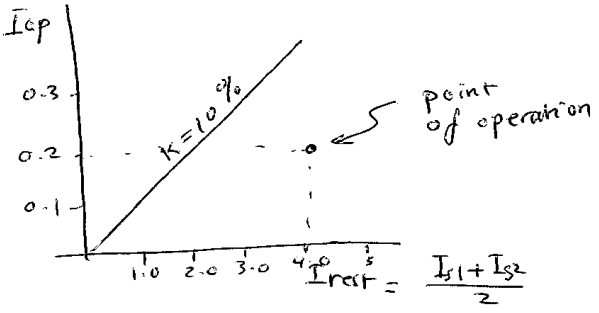
- For the relay to operate, the current in the operating coil must be not less than 10% of Irest.

$$I_{op} \overset{?}{>} K\left(\frac{I_1 + I_2}{2}\right)$$

$$I_{op} \overset{?}{>} \frac{10}{100} \times 4.1 = 0.41 \text{ A}.$$

Since $I_{op} = I_{S1} - I_{S2} = 4.2 - 4.0 = 0.2$

Hence the current through the relay operating coil will not be sufficient to operate the relay.




DP/11

## Transmission Lines and Feeders Protection

- **Pilot wire differential relays (Device 87L)**
- **Distance protection**

# 1. Pilot wire differential relays (Device 87L)

The pilot wire differential relay is a high-speed relay designed for protection of transmission and distribution lines. They are generally applied on short lines, normally **less than 40 km long.**

The scheme requires communication channel (link) to carry system voltage and current information to the control location. The main objective of using pilot relaying is to remote control of the circuit breakers.

Four basic communication channels are used:

1. Separate telephone circuit (telephone wire or cable) this is called pilot wire carrier.

2. Microwave system using directional dishes.

3. Fibre optic cable.

4. Power line carrier.

(a) Operating principles of a current pilot wire relay

Pilot wire differential relaying is a relay system consisting of two identical relays located at each end of a line (see Figure 1). The relays are connected together with a two-conductor pilot wire. The output from three individual phase CTs is applied to a summing transformer that produces a composite current which is proportional to the line current and has a polarity related to line current flow direction.

The circuit is basically that of the percentage (restraint) differential relay with the operating circuit broken into parallel circuits separated by pilot wires. This relay is available in both electromechanical and static designs.

- When the fault is external to the relay's protective zone, current flows in the pilot wire through each relay's restraint coils, but not through the relay's operating coil.
- If the fault is within the relay's protective zone and current is flowing into the fault from both directions, the direction of pilot wire current $I_{PA}$ remains the same; but the direction of current $I_{PB}$ reverses and forces current to flow into each relay's operating coil. If the fault current flows through circuit breaker *A* only, the relay at *A* still passes sufficient current through the pilot wire to operate the relay at circuit breaker *B*.

- Summing transformer is used to convert current signal to voltage signal.
- For faults outside the line from both sides at $F_1$ and $F_3$ , VA = VB , relay will not operate.
- For fault inside the line at $F_2$ , relay will operate, since VA ≠ VB.
- The pilot wire signal is about 30V ac at 50 Hz or 20V ac at 60 Hz.

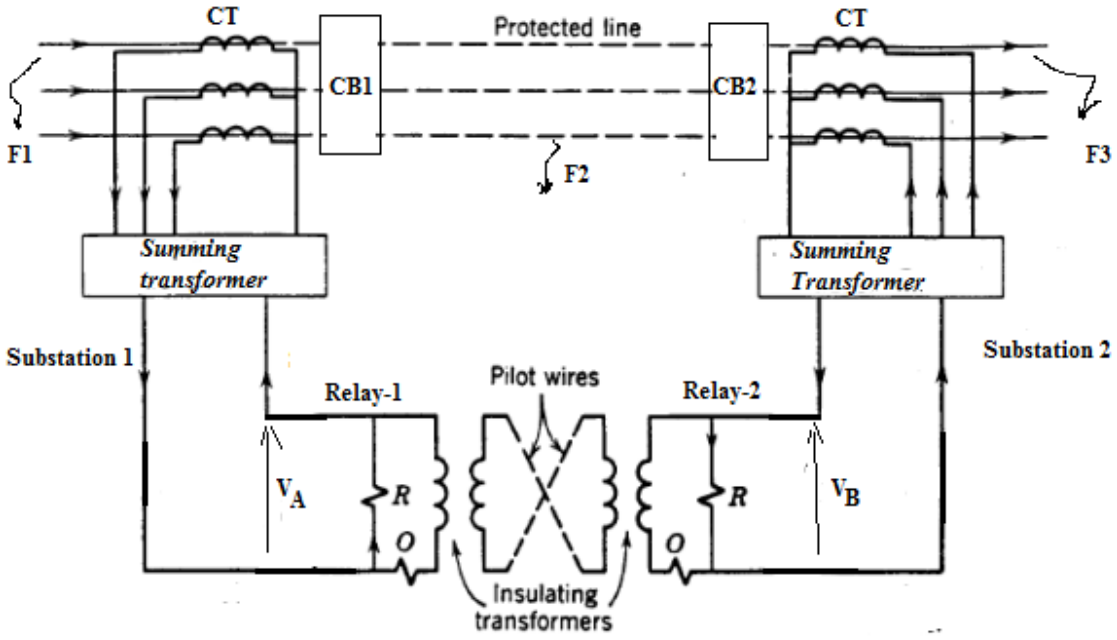



Fig.1 Pilot relaying of short transmission line . R=voltage restrain coil; O= current operating coil.

## (b) Power Line Carrier (PLC)

In power line carrier protection scheme, a high frequency signal in the band of 80-500 kHz and of low power lever is transmitted via the power line conductors from each end of the transmission to the other.

Signal is received by either end of the line by a receiver R to give tripping or blocking orders to the circuit breaker. The system is shown in Fig.2.

- The high frequency is injected to the power line by a coupling capacitor.
- The signals are confined to the line by an LC blocking filter at each end. This is called a line trap. Line trap is shown in Fig.3.
- This means that the power transmission line is used as the communication channel (circuit).

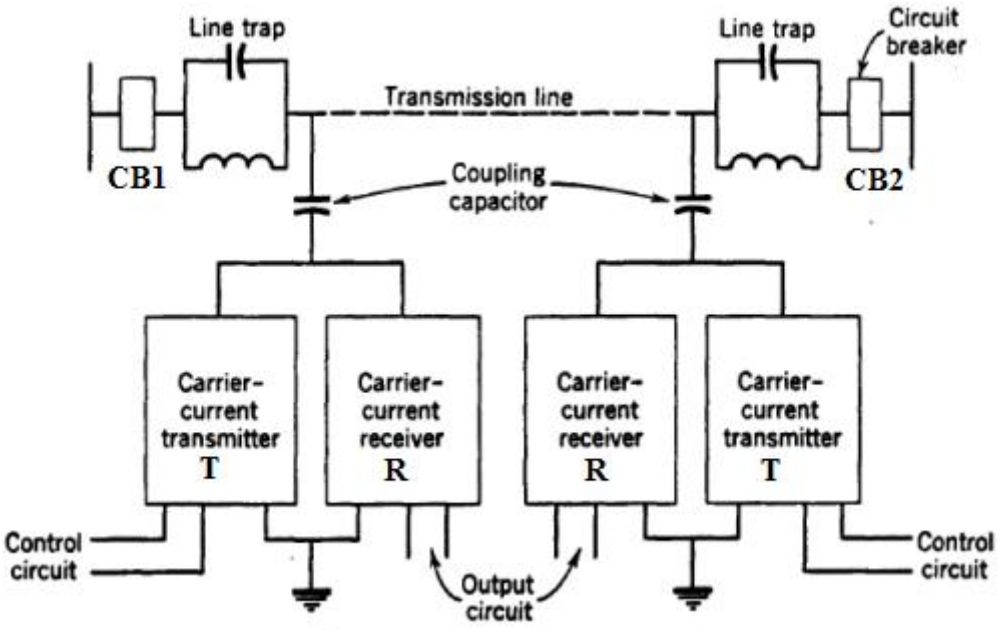



Fig.2 Power line carrier system.

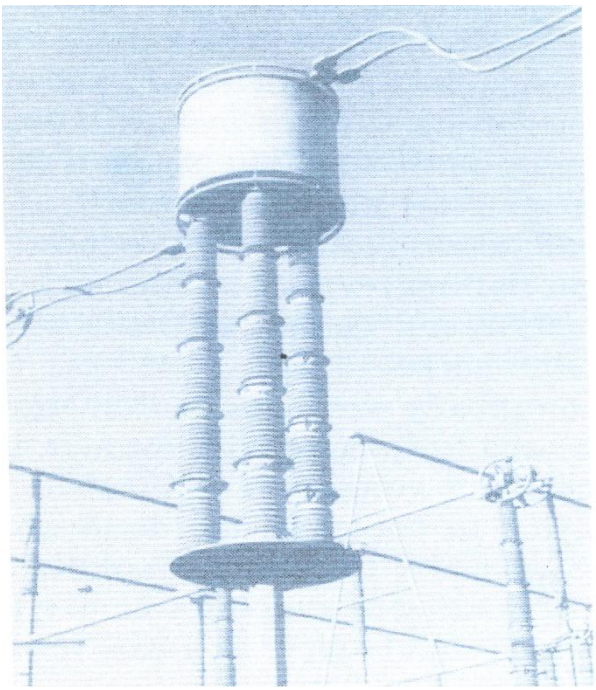


Fig.3 A 500kV Line Trap.

# 2.Transmission Line Protection: Distance Relay

Transmission line protection by pilot wires (pilot relaying) is limited to 30 to 40 km in rout length. For longer transmission lines and subtransmission lines or even distribution feeders, distance protection is used.

## Principle of Distance Protection

The term *distance* is used for a family of relays that respond to a ratio of voltage to current and therefore to impedance or component of impedance .Distance relay may have the following features:

- A distance relay has the ability to detect a fault within a pre-set distance along a transmission line from its location.
- Every power line has a resistance and reactive per kilometer related to its design and construction so its total impedance will be a function of its length or distance.
- A distance relay therefore looks at current and voltage and compares these two quantities on the basis of Ohm's law (see Figure 1).
-

Consider the simple radial line with distance protection system installed at the end A (the local end) while end B is called the remote end. These relays sense local voltage and current and calculate the effective impedance at that point. This means that the relay requires voltage and current information.

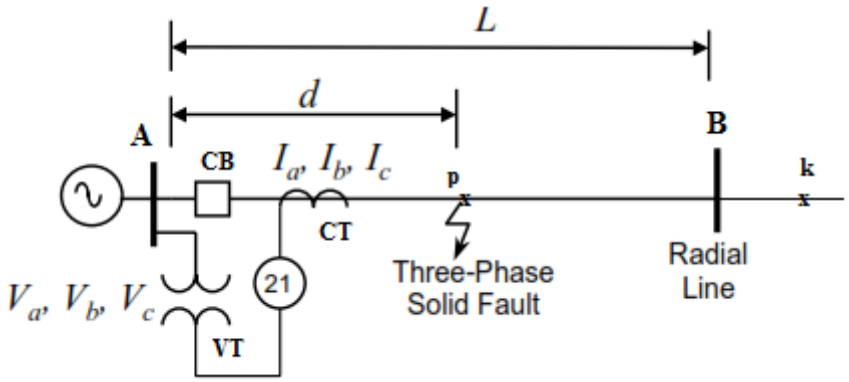



Fig.1

When the protected line becomes faulted, the effective impedance becomes the impedance from that point to the fault.

Assume balanced three-phase fault at distance d:

- For internal fault at point p :
  $Z_p = \frac{V_p}{I} < Z_L$ Relay will operate

- For external fault at point k :
  $Z_p = \frac{V_k}{I} > Z_L$ Relay will not operate

In general the relay will trip when $Z_f = \frac{V}{I} < Z_L$ where $Z_f$ is the impedance at the fault point which is $\propto$ line length. For example at point *p:* $Z_{fp} = \frac{d}{L} Z_L$ .

Hence the distance relay action is to compare the local voltage with the local current, i.e. the secondary values of V and I in the voltage and current transformers so as the quantity $\left(\frac{V}{I}\right)$ …is the measured impedance $Z_m$ where,

$$Z_m = \frac{\frac{V}{VT\ ratio}}{\frac{I}{CT\ ratio}} = \frac{V}{I} x \frac{CT\ ratio}{VT\ ratio} = Z_f \frac{CTratio}{VT\ ratio}$$

Where $Z_m$ is the measured impedance (appears at the relay terminal) also called the **secondary impedance.**

and $Z_f$ is the also called the **primary impedance.**

## Types of Distance Relays

In general there are four main types of distance relays

- Impedance relay (Ohms relay)
- Admittance relay ( Mho relay)
- Reactance relay
- Offset Mho relay

➢ Impedance relay can also be of two types: a **plain** relay or **directional** type. It can be constructed as electromagnetic like the balanced beam relay or static type like the bridge comparator relay. Also digital impedance relay is available.

➢ Admittance relay can be either static or digital types.

## Plain impedance relays:

### 1 - Balanced beam relay

- The concept can best be appreciated by looking at the pioneer-type balanced beam relay (see Figure 2). The voltage is fed onto one coil to provide restraining torque $T_r$ , whilst the current is fed to the other coil to provide the operating torque $T_o$.
- Under healthy conditions, the voltage will be high (i.e. at full-rated level), whilst the current will be low (at normal load value), thereby balancing the beam, and restraining it so that the contacts remain open.
- Under fault conditions, the voltage collapses and the current increase dramatically, causing the beam to unbalance and close the contacts.

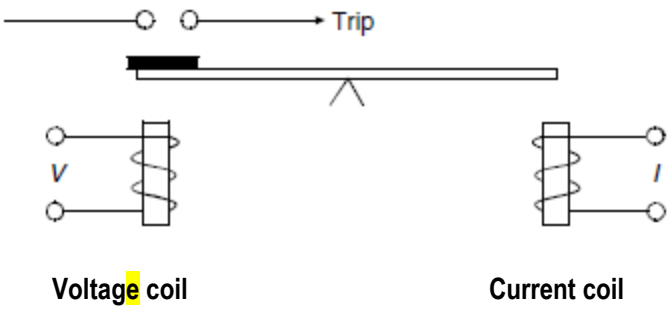



Fig.2 Balanced beam relay used as a distance relay.

For voltage coil : $T_r = K_1 V^2$

For current coil : $T_o = K_2 I^2$

Where $K_1$ and $K_2$ are constants .

For balance case: $T_r = T_o$ or $K_1 V^2 = K_2 I^2$

For the contact of relay to close: $T_r < T_o$ or $K_1 V^2 < K_2 I^2$

$$\frac{V^2}{I^2} = \frac{K_2}{K_1} \qquad \frac{V}{I} < \sqrt{\frac{K_2}{K_1}} \qquad \text{or} \quad Z < \sqrt{\frac{K_2}{K_1}}$$

Hence, the relay will operate when the impedance it 'sees' is less than a predetermined value.

## Tripping characteristics of distance relay

If the relay's operating boundary is plotted, on an *R-X* diagram, its impedance characteristic is a circle with its center at the origin of the coordinates and its radius will be the setting in ohms (Figure 3).

The relay will operate for all values less than its setting i.e. is for all points within the circle. This is known as a plain impedance relay and it will be noted that it is non-directional, in that it can operate for faults behind the relaying point. It takes no account of the phase angle between voltage and current.

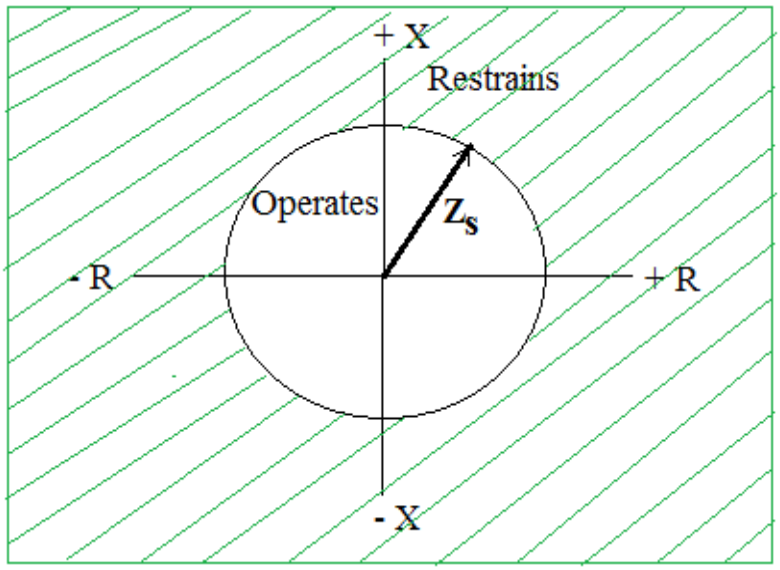


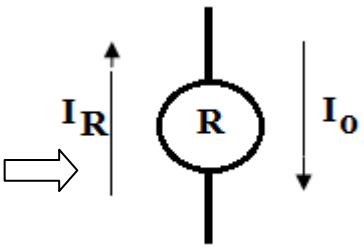

Fig.3 Plain impedance characteristic.

### 2. Bridge comparator static impedance type distance relay

A more modern technique for achieving the same result is to use a bridge comparator distance relay (see Figure 4).

Referring to Fig.4:

- VT output is converted to a current $I_R$ which is the restrain current due to $Z_R$ .
- CT provide the operating current Io .
- $I_R$ and Io are converted to scalar values by two rectifiers , and the relay current is the numerical difference of the two currents .



- If the current through the relay is greater than the setting current , it will cause the relay to close the contacts (**operates**).
- If at the remote point B, the restrain current is approximately equal to the operating current, the relay **will not operate**.
- During an internal fault (0 – 80% in Zone 1) , the relay current should be several times the setting current to ensure its fast operation, the operation should be within 60 ms time .

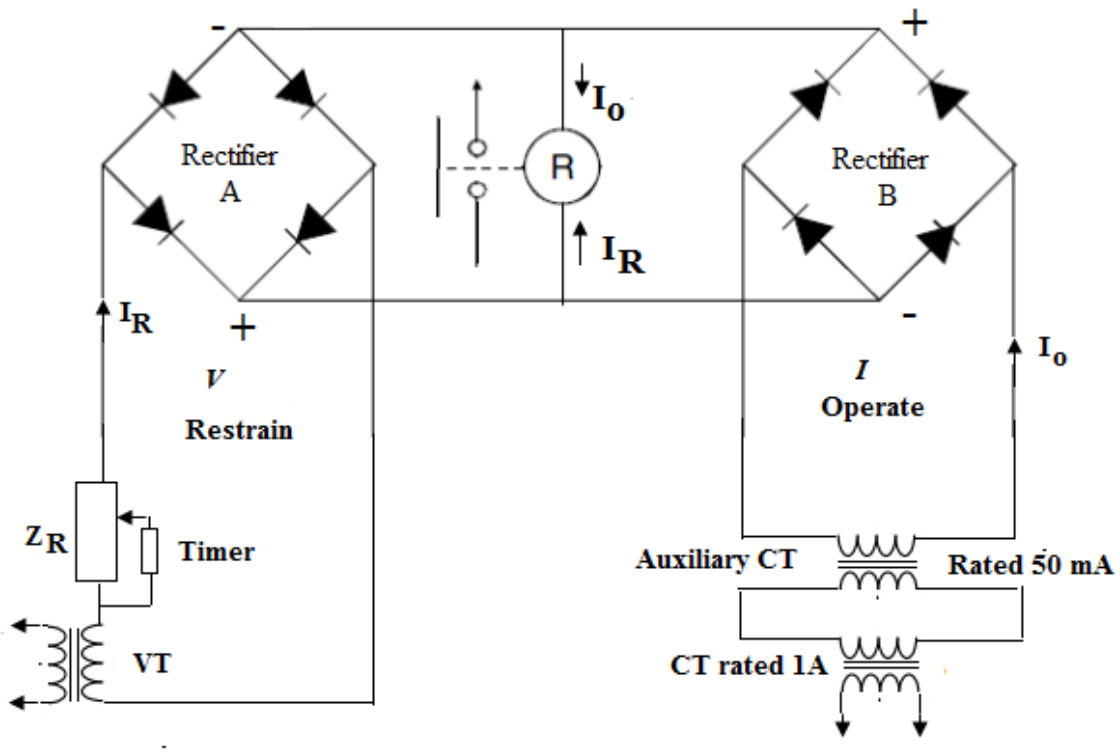



**Fig.4** Bridge comparator in modern distance relay.

**Notes :**

- The impedance relay does not consider the phase angle between the voltage and current applied to it.
- The relay operates for all impedance values that are less than its setting (all the values inside the circle shown in Fig.3).
- It restrain for all values (points) outside the circle.

### Relay Reach, underreach and overreach

The reach of the distance relay is that distance from the relaying point to the point of fault. The reach is usually refers as the relay setting and can be as a distance (m), or as a primary or secondary impedance.

## Relay reach adjustment

Referred to Fig.2, by changing the ampere-turns relationship of the current coil to the voltage coil, the ohmic reach of the balanced - beam relay can be adjusted. A more modern technique for achieving the same result is to use a bridge comparator (see Figure 4).

### Advantage of distance relay:

1. Provide backup protection easily.

2. Eliminates the pilot channel.

### Features

- Distance protection is available for both phase and ground faults.
- Step distance protection combines instantaneous and time delay tripping.

### Zones of protection

- Due to the tolerance in the circuit components, the measuring accuracy cannot be perfect so it is usual to set the relay at the local point A at 80% of the secondary impedance of AB. This is referred as zone 1 or stage A1 setting (see figure 5).
- The remaining 20% of AB is protected by by changing the setting of the relay to reach 50% into zone BC (zone 2 or stage A2). Stage A2 is usually set at 0.3 s time.
- For system reliability (failure of relay A will cause failure of stage A1 and stageA2), another distance relay is added for backup protection. This separate relay should have a reach of 20% into CD and called zone 3 or stage A3 which has a time delay of 0.6 s.

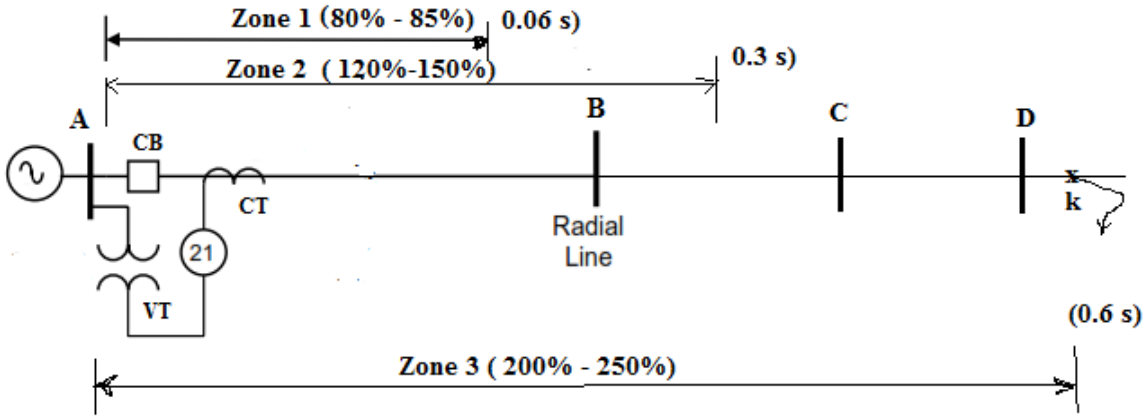



Fig.5 A three- sage distance protection system.

**Notes:**

- Zone 1 is an underreaching element, any fault within Zone 1 is known to be on the protected line. When Zone 1 operates, the line is tripped instantaneously.
- Zone 2, however, will operate for some external faults.

Summary:

**Discrimination zone (or setting zone) by:**

$$Z_1 protection\,(0.80\% - 0.85\%)$$
$$Z_2 protection\,(120\% - 150\%)$$
$$Z_3 protection\,(200\% - 250\%)$$

**Example 1:** For the 66kV radial feeder shown in Fig.6, Calculate zone 1 setting for the distance relay in primary ohms.

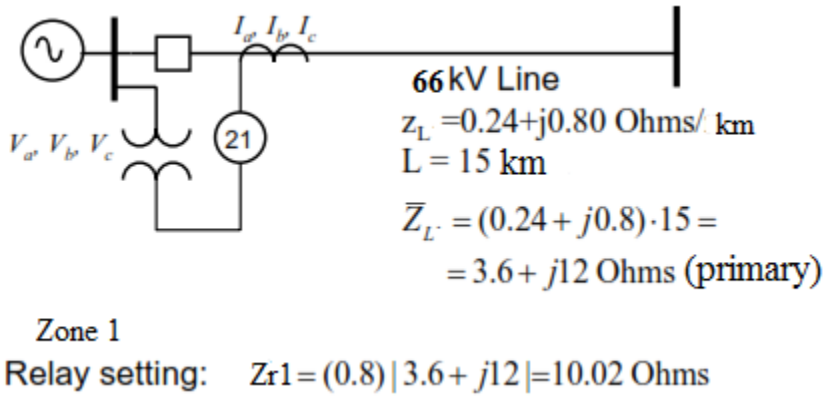

$I_a, I_b, I_c$
66 kV Line
$z_L$ =0.24+j0.80 Ohms/ km
L = 15 km
$\overline{Z}_L = (0.24 + j0.8)\cdot 15 =$
$= 3.6 + j12$ Ohms (primary)
$V_a, V_b, V_c$
21
Zone 1
Relay setting: $Zr1 = (0.8)\,|3.6 + j12| = 10.02$ Ohms

Fig.6

---

**Example 2:**

Figure 7 shows a simple two radial lines. We will consider the settings for line *AB* at bus *B*. The impedance angle for each line is 75°. The line length is 80 km, the distance relay at bus *A* is fed by current transformers rated at 2000 A: 5 A and voltage transformers rated at 345 kV/200 kV Y: 120 V/69 V Y. Find the settings of zone 1 and zone 2 of the relays.

Solution

Set Zone 1 for 85 %:

Zone 1 setting = 0.85 x 80 = 68 ohm, primary ohm setting ($Z_{fp}$)

CT ratio = 2000/5 = 400

VT ratio = 200,000/69 = 2900

Relay setting for zone 1 = $Z_{fp}$ . CT ratio/VT ratio

= 68 (400)/(2900)

= 9.38 relay ohms

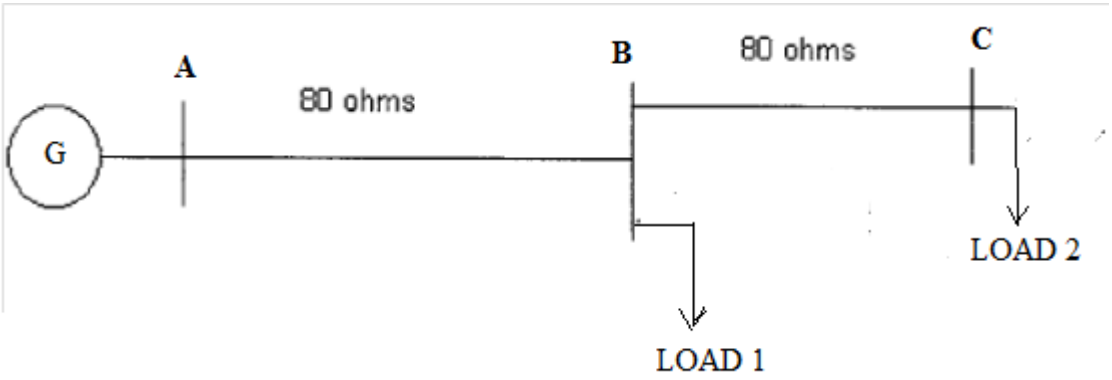



Fig.7

Zone 2 setting : 120 % -150% Choose 140% ;

Zone 2 setting _=1.40 x 80 = 112 ohm, primary ohm setting ($Z_{fp}$)

Relay setting for zone 2 = $Z_{fp}$ . CT ratio/VT ratio

=112 (400)/(2900)

= 15.44 relay ohms

---

Example-3 Consider the 230-kV transmission system shown in Fig.8. Assume that the positive-sequence impedances of the lines L1 and L2 are 2 + j 20 Ω and 2.5 + j 25 Ω, respectively. If the maximum peak load supplied by the line L1 is 100 MVA with a lagging power factor of 0.9, design a three-zone distance-relaying system for the R12 impedance relay by determining the following:

(a) Maximum load current

(b) CT ratio and VT ratio

(c) Impedances measured by relay

(d) Zone 1 setting of relay R12

(e) Zone 2 setting of relay R12

(f) Zone 3 setting of relay R12

(g) Draw the zones of protection for R12 and suggest time settings for the three zones.

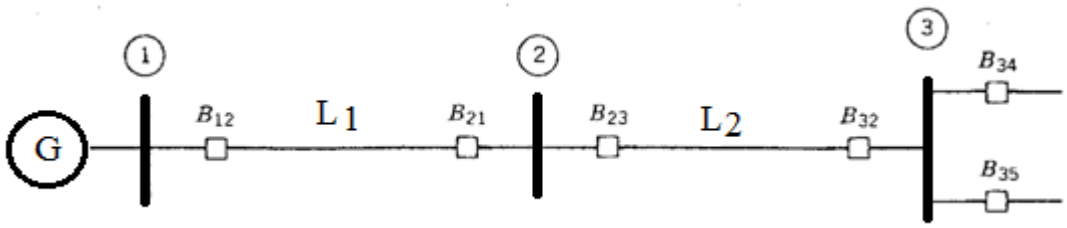



Fig.8

Solution :

(a) Max.load current = $\frac{S}{V\sqrt{3}} = \frac{100x10^6}{230\ x\ 10^3\ \sqrt{3}}$ = 251.02 A

(b) Choose: CT ratio = 250 / 5

VT ratio $= \frac{230\ x\ 10^2}{120} = \frac{1916.7}{1}$

(c) Impedances measured by relay is

$$Z_{sec} = Z_{prim}\ x\ \frac{CT\ ratio}{VT\ ratio} = \frac{250/5}{1916.7/1}\ Z_{prim} = 0.026\ Z_{line}$$

Impedance of line L1and line L2 as seen by the relay (Line impedances based on secondary ohms) are:

$Z_{sec\ -\ L1}$ = 0.026 (2+j20) = 0.52 + j 0.5196 Ω

$Z_{sec\ –\ L2}$ = 0.026 (2.5+j25) = 0.65 + j 0.6495 Ω

(d) Zone 1 setting of relay R 12 is

Z1 = 0.8 (0.52 + j 0.5196 )= 0.0416 + j 0.4157 sec. Ω

(e) Zone 2 setting of relay R 12 is

Z2 setting is = 120% - 150% , Choose 140%

Z2 = 1.4 (0.52 + j 0.5196 )= 0.0728 + j 0.727 sec. Ω

(f) Zone 3 setting of relay R12 : Since the zone 3 setting must reach beyond the longest line connected to bus 2 ,thus

Z3 = 120% ($Z_{sec\ -\ L1}$ + $Z_{sec\ –\ L2}$) = 1.20 (0.52 + j 0.5196 + 0.65 + j 0.6495) = 0.1400 +j 1.402 sec. Ω

(g) Draw the zones of protection for R12 and suggest time settings for the three zones.

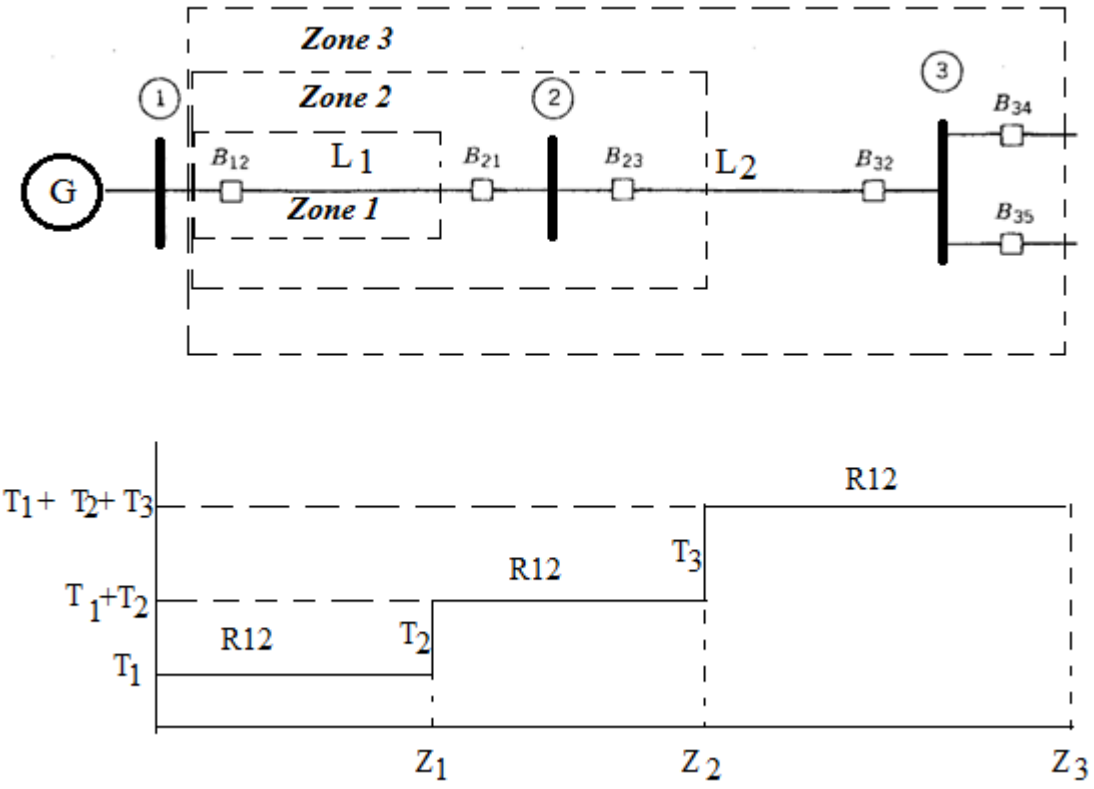



Fig.9

Is the distance relay of plain impedance type is directional?

The impedance relay is non-directional that is, it operates for all faults along the vector AB in Fig.10 such as point p and also for all faults behind the bus A up to impedance AC such as point k.

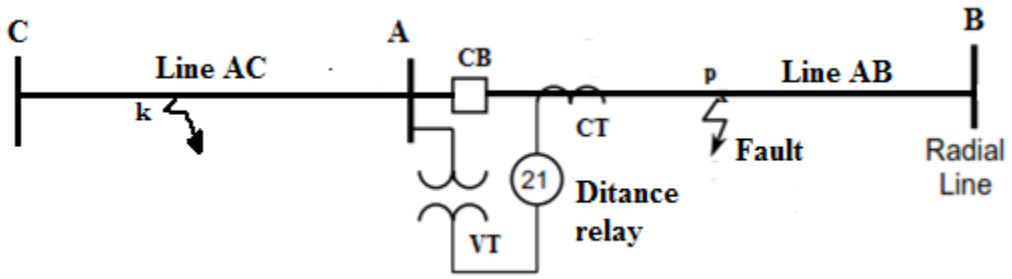



Fig.10

A directional unit may be added to the plain impedance distance relay to make it operate in one direction only as depicted in Fig.11.

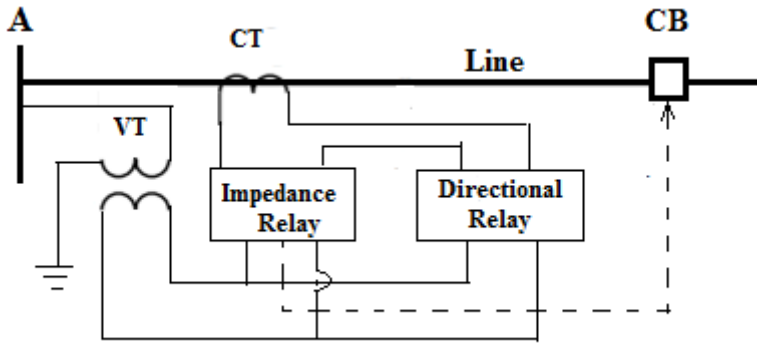



Fig.11 Typical per-phase arrangement for a three – zone distance relay with directional unit .The directional unit may be a wattmetric relay.

# Transformer Protection

# Transformer Protection

The protection method used for power transformers depends on the transformer ratings. Transformers are usually categorized according to their ratings as follows:

| Category | Transformer Rating – KVA | |
|---|---|---|
| | 1 Phase | 3 Phase |
| I | 5 – 500 | 15 – 500 |
| II | 501 – 1,667 | 501- 5,000 |
| III | 1668 – 10,000 | 5,001 – 30,000 |
| IV | > 10,000 | > 30,000 |

- Transformers below 5000 KVA (Category I & II) are protected using Fuses.Fuses and MV circuit breakers are often used to protect transformers up to 1000 kVA (distribution transformers for 11kV and 33kV).

- For transformers 10 MVA and above (Category III & IV) ,differential relay are commonly used to protect them. Current differential relays are applied for transformers as main protection. In regard to backup protection, distance protection or overcurrent (phase current, zero sequence current) protection or both are mainly applied.

In addition to the above, mechanical relays such as **Buchholtz** relays and sudden pressure relays are widely applied to transformer protection, and are particular to application to transformer protection. Mechanical relays are intended to detect faults which the main relay could not detect. In addition to these relays, thermal overload protection is often applied for the purpose of extending a transformer's life time rather than for detecting faults.

# Main Electrical Protection

(1) Percentage Biased Current Differential protection

Differential Protection provides the best overall protection. Biased current differential protection is most commonly applied for transformer protection. **Fig.1** shows typical application for a star-delta transformer. **Fig.2** shows typical connections of the percentage differential relays with their associated current transformers.

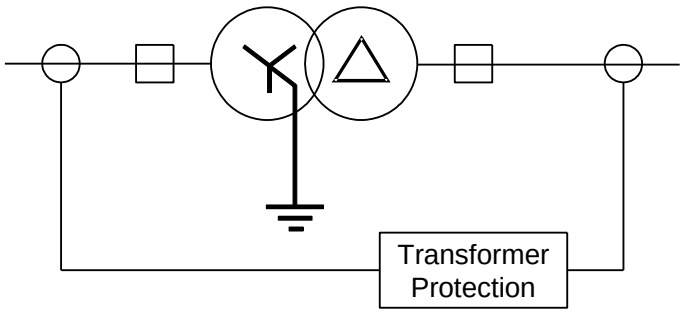



**Fig.1 Typical Application**

# Transformer Differential Relay Connections

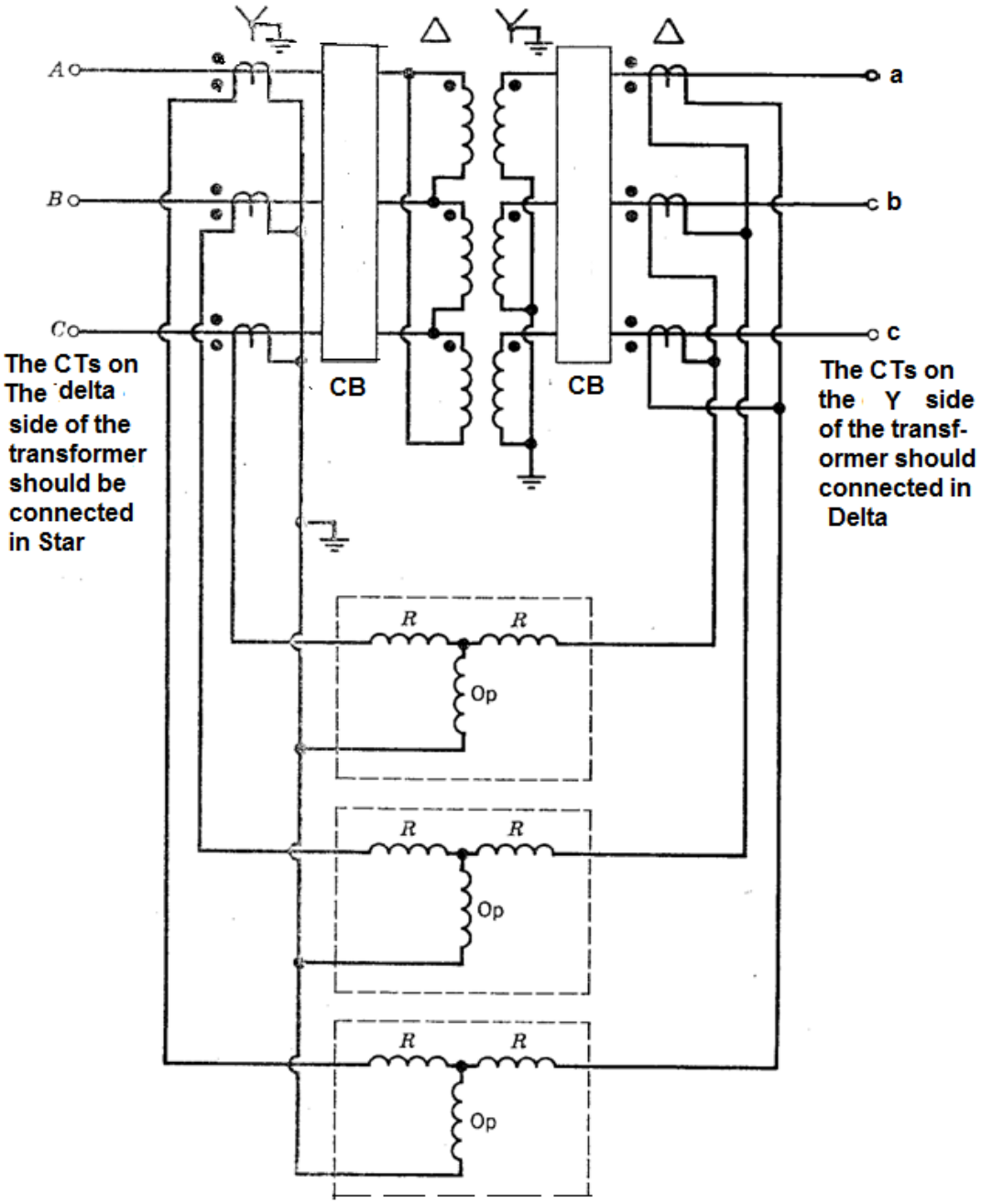



**Fig.2 Protection of delta – Star transformer bank by percentage differential relays.**

## Phase Shifting in Star-Delta Connected Transformer

Between the primary and secondary current of the transformer of a star-delta connection is a phase angle difference of 30°. For this reason, a method that aligns the current phase by differing from the connection of the CT secondary circuit of both sides is taken. The following describes the concept of such a connection.

The transformer unit is connected to the CT secondary circuit on the star connection side by a delta connection and to the CT secondary circuit on the delta connection side by a star connection, thereby acquiring a correct phase relationship with respect to load current and external fault current. **Fig.2** shows the correct phase relationship with respect to a three-phase current.

### (2)Restricted Earth Fault Protection

A very large fault current can flow when a fault occurs at the transformer bushing. In that case, the fault must be cleared as quickly as possible. It can be difficult for phase current differential protection to detect faults to earth near transformer neutral points. In this case zero sequence current differential protection comparing the neutral current with the residual current of three phases, which is often called restricted earth fault protection (**REF**) is suitable to be applied. This function can be combined with phase current differential protection in a single unit as shown in **Fig.3**.

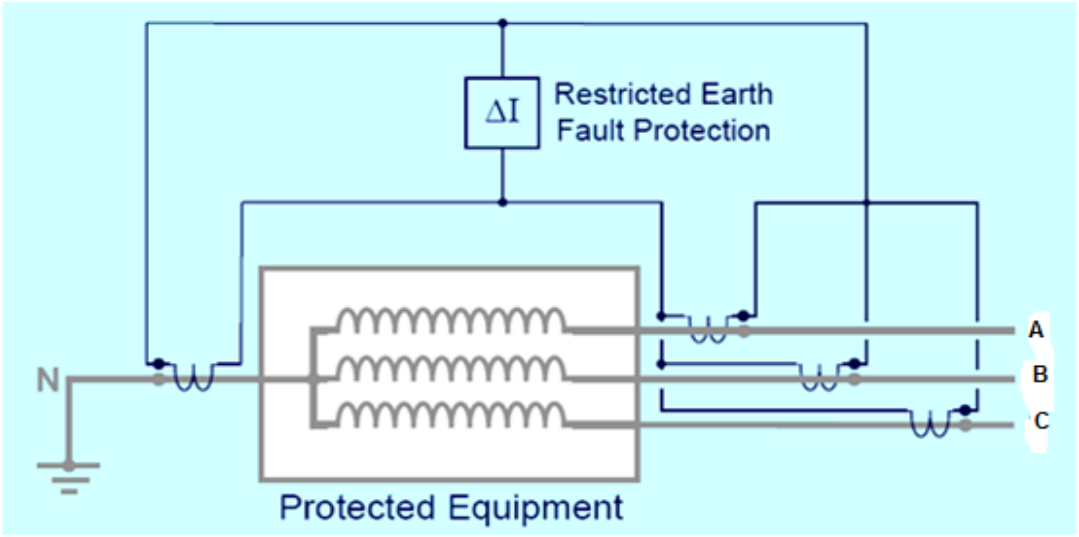



**Fig.3 Typical Application with REF.**

## Example

Assume that a three-phase delta–wye-connected, 30-MVA, 69/34.5-kV power transformer is protected by the use of percentage differential relays, as shown in Figure 7.70. If the CTs located on the delta and wye sides are of 300/5 and 1200/5 A, respectively, determine the following:

(a) Output currents of both CTs at full load.
(b) Relay current at full load.
(c) Minimum relay current setting to permit 25 percent overload.

*Solution*

(a) The high-voltage side line current is

$$I_{HV} = \frac{30 \times 10^6}{\sqrt{3}(69 \times 10^3)} = 251.02 \text{ A}$$

The low-voltage side line current is

$$I_{LV} = \frac{30 \times 10^6}{\sqrt{3}(34.5 \times 10^3)} = 502.04 \text{ A}$$

Therefore, the output current of the CT located on the high-voltage side is

$$251.02\left(\frac{5}{300}\right) = 4.1837 \text{ A}$$

and the output current of the CT located on the low-voltage side is

$$502.04\left(\frac{5}{1200}\right)\sqrt{3} = 3.6232 \text{ A}$$

Note that the winding current of the delta-connected CT is multiplied by $\sqrt{3}$ to obtain its line current.

(b) The relay current at full load is

$$4.1837 - 3.6232 = 0.5605 \text{ A}$$

(c) Thus, the minimum relay current setting to permit 25 percent overload is

$$(1.25)(0.5605) = 0.7007 \text{ A}$$

## Backup Protection

### (1) Overcurrent Protection

It is quite common that overcurrent relays are applied to the high voltage side for transformer backup protection. It is especially suitable when there is no power source on the lower voltage side, because the overcurrent protection will operate only for faults in the transformer or on the low voltage side. Inverse overurrent relays are sometimes applied to the lower voltage side for back up protection for the lower voltage lines rather than for the transformer.

### (2) Distance Protection

If VTs are available, distance relays can be applied for backup protection. An advantage of distance protection is that it can distinguish forward faults from reverse faults. Therefore, distance protection can be applied for backup protection even when there are power sources on the lower voltage side. It is also possible that distance protection is applied as second main protection of a transformer if the zone 1 reach is set to less than the total impedance of the transformer. (e.g. 80%)

# Mechanical Protection

Insulation deterioration of the electrical circuit or the iron core may cause vaporization of insulation fluid. Since differential protection for transformer cannot detect such an event, the following mechanical protection should be used.

### (1) Buchholtz Relay

The Buchholtz relay is installed at the pipe between the main unit and the conservator, and it detects resolved gas by the float switch when a fault occurs within the transformer.

- A Buchholz relay is a gas and oil operated device installed in the pipe between the top of the transformer main tank and the conservator.
- The function of the relay is to detect an abnormal condition within the tank and send an alarm or trip signal.

- Under normal conditions the relay is completely full of oil. Operation occurs when floats are displaced by an accumulation of gas, or a flap is moved by a surge of oil.
- Almost all large oil-filled transformers (above 500kVA – category-II) are equipped with a Buchholz relay. A general view of the relay is shown in Fig.1.

Fig.1 Buchholz relay Front View (A - Gas Collection Chamber).

**Principle of operation**

A Buchholz relay will detect:

- Gas produced within the transformer
- **An oil surge from the tank to the conservator**
- A complete loss of oil from the conservator (very low oil level)

Fault conditions within a transformer produce gases such as carbon monoxide, hydrogen and a range of hydrocarbons.

- ❖ A small fault produces a small volume of gas that is deliberately trapped in the gas collection chamber (A) built into the relay. The oil level will be lowered and the oil in the bucket (B) will tilt the

counter weight C.W., thus switch Hg1 operates alarm circuit to send an alarm (see Fig.2.

- A large fault produces a large volume of gas which drives a surge of oil towards the conservator. This surge moves a flap (P) in the relay to operate switch Hg2 and send a trip signal to open the main circuit breaker.
- The device will also respond to a severe reduction in the oil level due to oil leakage from the tank.

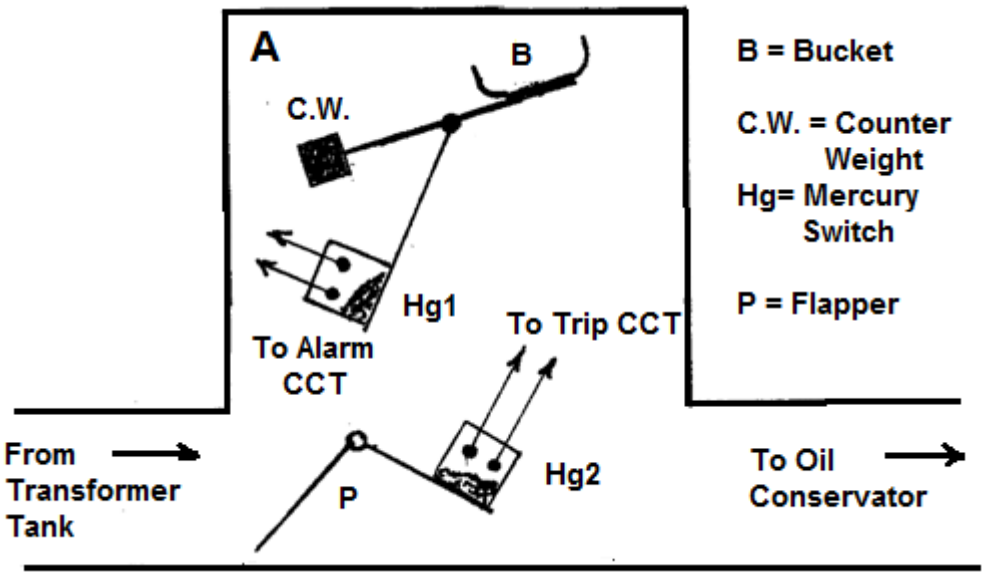
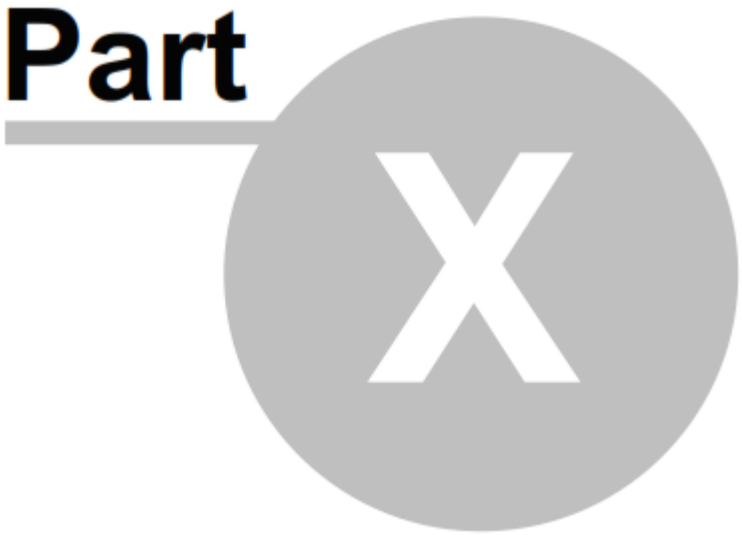



**Fig.2 Construction of Buchholz relay.**

## (2) Sudden-Pressure Relay

The sudden-pressure relay is installed in the upper part of a bursting tube, and it detects the sudden increase of internal pressure by the bellows when a fault occurs within the transformer.




# GENERATOR PROTECTION

# MOTOR PROTECTION

# BUS PROTECTION

# GENERATOR PROTECTION

- The generator protection system design should take into account the types of faults and abnormal operating conditions that could be present at the generating plant and provide means for detecting and acting upon these conditions. The protection system design will depend on the size of the generating unit.

These fault types and disturbance conditions are classified as:

- Overload protection, and Overcurrent (short-circuit) problems
- Stator electrical faults
- Rotor electrical faults
- Failure of prime mover (mechanical problems)
- Failure of the field circuit

Hence we must protect the generator against the effect of these faults and abnormalities using the following protection schemes:

- Overload protection, and Overcurrent protection
- Overvoltage and undervoltage protection
- Overexcitation
- Unbalanced loading (Currents ) –sequence relay
- Loss of Excitation
- Loss of synchronism
- Phase Faults
- Earth Faults
- Abnormal Frequencies
- Motoring
- Overspeeding
- Excessive vibration
- Internal faults,
- Stator and rotor thermal protection, and
- Field ground.

## 1. Generator protection using differential protection schemes

To protect the generator against the failure of winding insulation and the failure of the field circuit as well as the primemover failures, differential protection is used with biased circulating current scheme. The theory of circulating current differential protection is discussed fully in part 7. The protection scheme is shown in Fig.1.Normally differential protection is used for generators larger than or equal to 20MW.

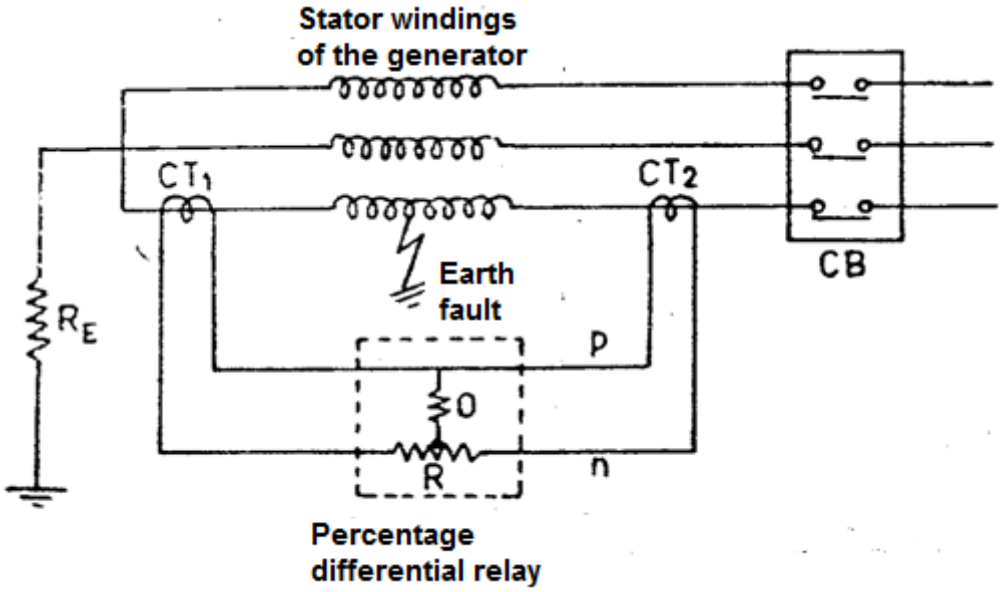



Figure 1: Stator biased differential protection for generator.

Example 1

Figure 2 shows a biased percentage differential relay applied for the protection of synchronous generator windings. The relay has 0.1A minimum pick up current and a 10 %.

(a) Fault has occurred near the grounded neutral end of the generator when the generator is carrying load. As a result, the currents flowing at each end are as shown in the figure. Would the relay operate or not?

(b) would the relay operate at the given value of fault current in (a) above mif the generator was carrying no load ?

(c ) On the same diagram , show the relay opersting characteristics and the points that represent the operating and restraining currents in the relay for the two conditions.

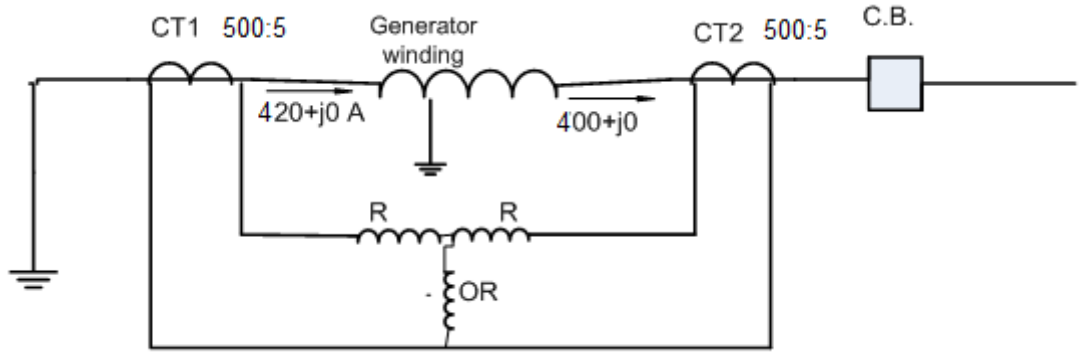
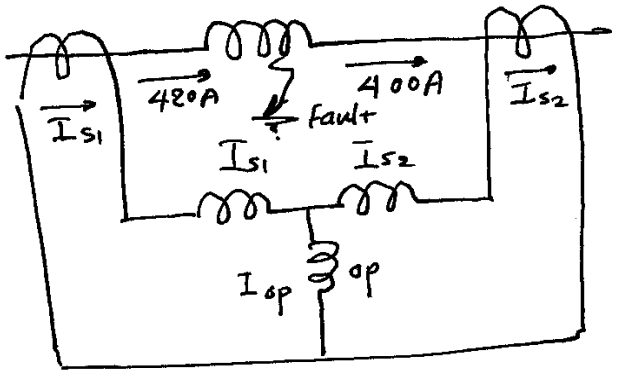



Fig.2

(a) Fault under load condition




$$I_{s1} = 420 \times \frac{5}{500} = 4.20\ A$$

$$I_{s2} = 400 \times \frac{5}{500} = 4.0\ A .$$

The restrain coil average current $I_r = \frac{I_{s1}+I_{s2}}{2}$

or $I_r = \frac{4.0+4.20}{2} = 4.1\ A .$

(For relay to operate, the current in the operating coil must not be less than 10% of the restrain current, i.e, $I_{op} \geq \left[\frac{10}{100} \times 4.1 = 0.41\ A\right]$).

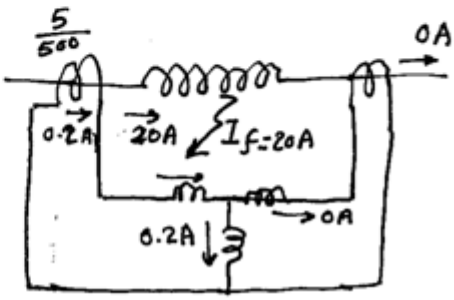
but $I_{op} = I_{s1} - I_{s2} = 4.2 - 4.0 = 0.2\ A$ which is less than 0.41 A., Therefore, the relay will not operate.

(b) Generator under fault at no load :

Under no load condition, the fault current is the same as (a), hence:

$I_f = 420 - 400 = 20\ A$ .

$I_{f_s} = 20 \times \frac{5}{500} = 0.2A$ which flows through the operating coil.




$I_{s_2} = 0$.

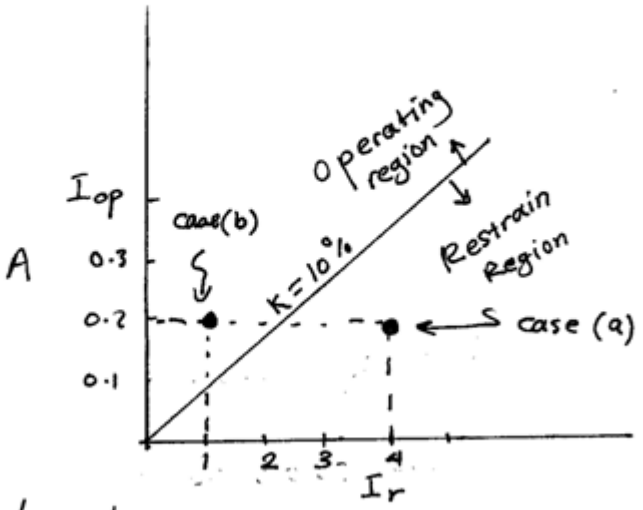
$I_{s_1} = I_{f_s} = 0.2\ A$

$I_{op} = I_{s_1} - I_{s_2}$

$= 0.2 - 0 = 0.2\ A$

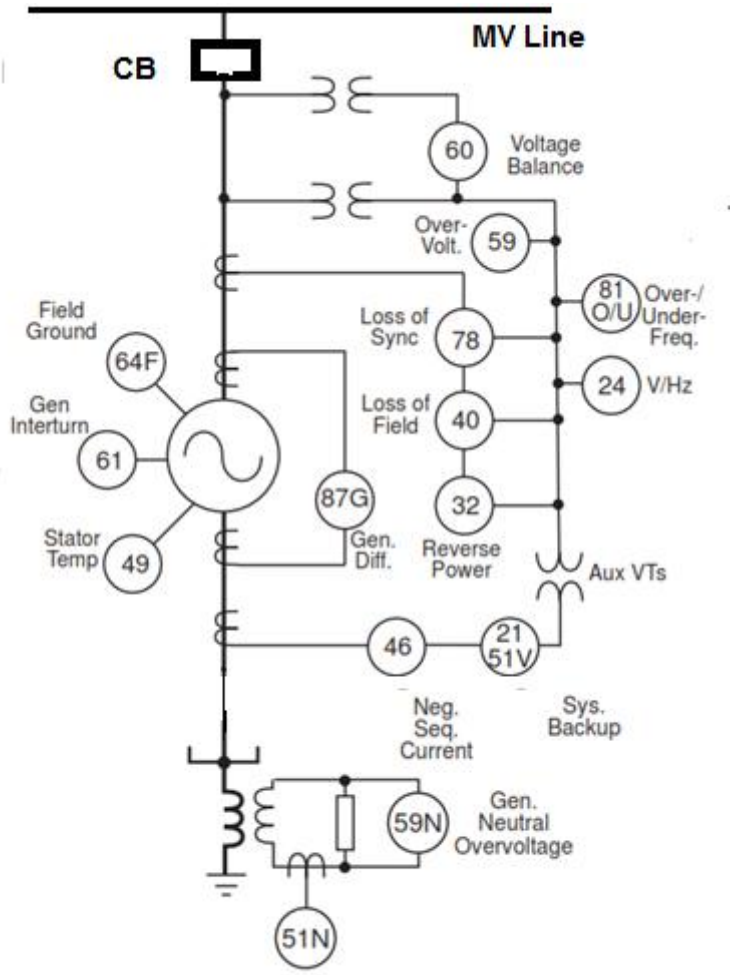
$I_r = \frac{I_{s_1} + I_{s_2}}{2} = \frac{0.2 + 0}{2} = 0.1\ A$ .

since $I_{op} > I_r$ hence the relay will operate.




Relay characteristics.

Typical generator protection scheme is shown in Fig.4 below:




Relay 51N or 51GN : Time overcurrent earth fault in the neutral

Fig.4 Generator Protection Application Simplified One-Line Diagram

## GENERATOR PROTECTION APPLICATIONS
## PHASE FAULT PROTECTION

Phase faults in a generator stator winding can cause thermal damage to insulation, windings, and the core, and mechanical torsional shock to shafts and couplings. Trapped flux within the machine can cause fault current to flow for many seconds after the generator is tripped and the field is disconnected.

## GROUND-FAULT PROTECTION

One of the main causes of ground faults is insulation failure. The zero sequence impedance of a generator is usually lower than the positive or negative sequence impedance, and hence, for a solidly grounded generator, the single phase to ground-fault current is greater than the threephase fault current. To limit the ground-fault current, generators are usually grounded through an impedance.

## LOSS-OF-FIELD (EXCITATION) PROTECTION

Loss of excitation on a synchronous machine can be caused by operator error, excitation system failure, a short in the field leads, accidental tripping of the field breakers, or flashover of the exciter commutator. When the machine loses its excitation, the rotor accelerates and the synchronous machine operates as an induction generator. As a result, the machine draws inductive reactive power from the system instead of supplying it to the system. Also heavy currents are induced in the rotor teeth and wedges and can cause thermal damage to the machine if the machine continues to operate.

## OVEREXCITATION PROTECTION

When the ratio of the voltage to frequency (volts/Hz) exceeds 1.05 pu for a generator, severe overheating can occur due to saturation of the magnetic core of the generator and the subsequent inducement of stray flux in components not designed to carry flux. Such overexcitation most often occurs during start-up or shutdown while the unit is operating at reduced frequencies, or during a complete load rejection which leaves transmission lines connected to the generating station. Failure in the excitation system can also cause overexcitation. Similar problems can occur with the connected transformer.

## OVERVOLTAGE PROTECTION

Generator overvoltage may occur during a load rejection or excitation control failure. In case of hydrogenerators, upon load rejection the generator may speed up and the voltage can reach high levels without necessarily exceeding the generator's V/Hz limit. The overvoltage relay(59) is used to protect the generator from this condition.

## UNBALANCED CURRENTS

Unbalanced faults and other system conditions can cause unbalanced three-phase currents in the generator. The negative sequence components of these currents cause double-frequency currents in the rotor that can lead to severe overheating and damage. The negative sequence overcurrent function (46) is provided to protect the unit before the specified limit for the machine is reached.

## ABNORMAL FREQUENCY PROTECTION

- Over Frequency Protection

Full or partial load rejection can lead to overspeed of the generator, and hence, over frequency operation. In general, over frequency operation does not pose any serious problems and control action can be taken to reduce the generator speed and frequency to normal without tripping the generator. Generators are shipped with overspeed detectors. An over frequency relay can be used to supplement this overspeed equipment. The multifunction relays provide a two-setpoint over frequency relay (device 81O) that can be set to alarm or trip on an over frequency condition.

- Under Frequency Protection

Overloading of a generator, perhaps due to loss of system generation and insufficient load shedding, can lead to prolonged operation of the generator at reduced frequencies. This can cause particular problems for gas or steam turbine generators, which are susceptible to damage from operation outside of their normal frequency band.
The turbine is usually considered to be more restrictive than the generator at reduced frequencies because of possible mechanical resonance in the many stages of the turbine blades. If the generator speed is close to the natural frequency of any of the blades, there will be an increase in vibration. Cumulative damage to the blades due to this vibration can lead to cracking of the blade structure.

# MOTOR PROTECTION

## 1. General

Fuses , thermal overload relay and contactors has proved itself an effective and economical solution for small to medium-sized motors up to about 150 hp.Two basic protections are used for these motor:

- Thermal overload protection
- Short-circuit (overcurrent) protection

On larger, more expensive motors or when maximum motor utilization is required under varying operational conditions more sophisticated flexible and accurate microprocessor protection relays
should be considered. These relays typically include:

- Thermal overload protection,
- Short-circuit protection
- Start-up and running stall protection
- Phase unbalanced protection
- Single-phasing protection
- Earth fault protection
- Undercurrent protection

The present day concept is use of microprocessor-based numerical relays for both HV and LV motors (say beyond 50 kW), as the relays come with lot of features which allow them to be interchangeable, ensures site settings and give valuable feedback on the load details whether a trip occurs or not.

## 2. Typical protective settings for motors

### (a) Long- time pick-up

• (1.15) times motor full load current (FLA) times motor service factor for applications,encountering 90% voltage dip on motor starting
• (1.25) times motor FLA times motor service factor for applications encountering 80% voltage dip on motor starting.

### (b) Long-time delay

• Greater than motor starting time at 100% voltage and the minimum system voltage
• Less than locked rotor damage time at 100% voltage and the minimum system voltage

• On high-inertia drives, it is common for the start time to be greater than the locked rotor withstand time. Under these circumstances, set the time to permit the motor to start. Supplemental protection should be added for locked rotor protection. One example of this is a speed switch set at 25% of rated speed tripping through a timer to trip if the desired speed has not been reached in a pre-determined time.

**(c) Instantaneous pick-up**

• Not less than 1.7 times motor long-time pick up rated ampere (LRA) for medium-voltage motors
• Not less than 2.0 times motor LRA for low-voltage motors.

**(d) Earth-fault protection**

• Minimum pick-up and minimum time delay for static trip units
• Core-balance CT and 50 relays set at minimum for medium-voltage, low-resistance grounded systems
• Residually connected CT, and 50/51 for medium voltage, solidly grounded systems. Minimum tap and time dial equals 1 for 51 relay
• Minimum tap (not less than 5 A) for 50 relay.

## Motor protective device

- Molded Case Circuit Breakers (MCCB) are used for low voltage motors of high ratings.
- Miniature circuit breakers (MCB) for small motors.
- Fuses + contactor + thermal relay for L.V motors.
- For high voltage motor: H.V. circuit breaker and differential protection.

## Example

A 100 hp, 480 V, 0.85 p.f, 85% efficiency motor has starting up to 5.9 rated current up to 8S with voltage dip of 80% during starting. Select protection means for this motor.

Solution:

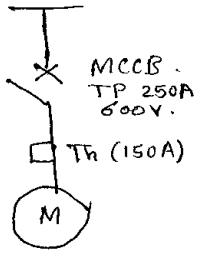
$$\eta = \frac{P_o}{P_{in}} \quad \therefore P_{in} = \frac{P_o}{\eta} = \frac{100 \times 746}{0.85} = 87.764 \text{ kW}$$

$$I_{rated} = \frac{P_{in}}{\sqrt{3} \times V \times P.f} = \frac{87764}{\sqrt{3} \times 480 \times 0.85} = 124 \text{ A}.$$

Choose Moulded case circuit breaker with both thermal and magnetic trips:

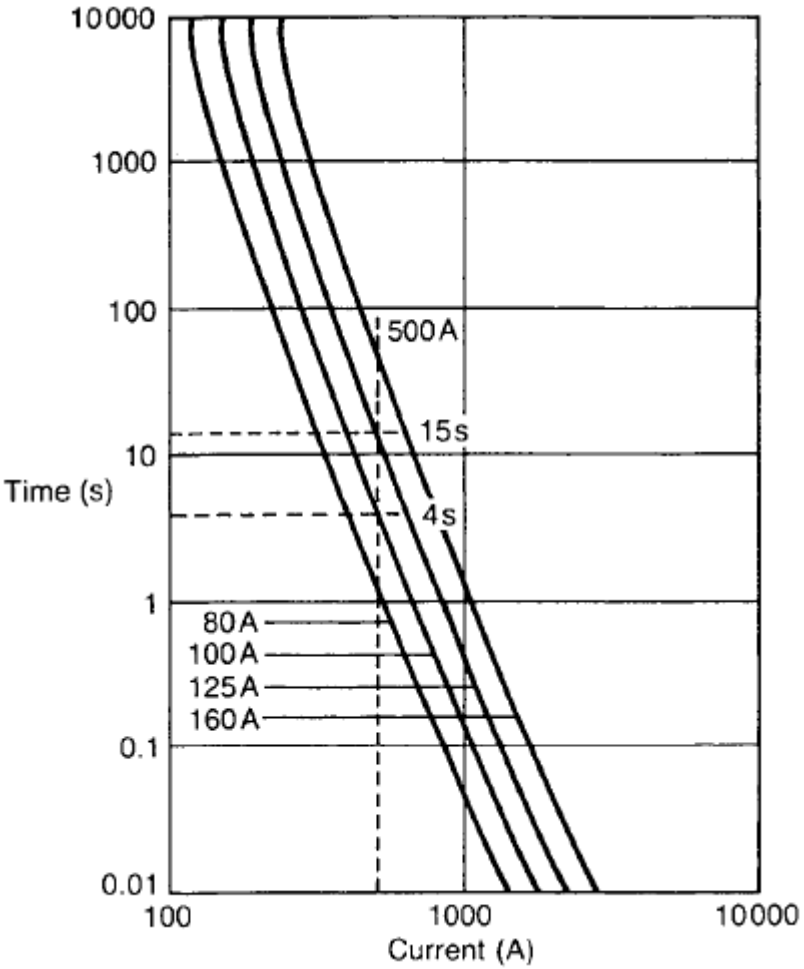
- Thermal setting of MCCB:
  Thermal pick up setting (100 – 125%) $I_{rated}$
  choose 125%.
  $\therefore$ Thermal setting = $1.25 \times 124 = 155$ A.
- Magnetic Trip = $6.75\ I_{rated} = 6.75 \times 124 = 837$ A.
- Circuit breaker rating = $2 \times I_{rated}$
  $= 2 \times 124 = 248$

Choose MCCB TP 250AF/150AT



# Motors protection by fuses

In several industrial applications, fuses are used for protecting small and medium size motors. To determine the fuse size for a motor, one should refer to Fig. 1 which shows typical fuse time/current characteristics. These characteristics represent fuse operation where the current is insufficient to operate the fuse in the first 1/4 - cycle,or 0.005 s in a 50 Hz system.




If the starting current of the motor is say 500 A and the run-up time 10s, then a 125 A fuse would be required. Examination of the fuse time/current characteristic shows that at 500 A the 125 A fuse would operate in 15 s. The fuse one size lower, 100 A, would operate in 4 s at 500 A and is, therefore, not suitable. The full-load current of the motor would be, say, 83 A and although a 100 A fuse would deal with this current it could not deal with the starting current for the duration of the starting time. The fuse does not protect the motor against overload as the rating of the fuse is always two to three times the full load current.

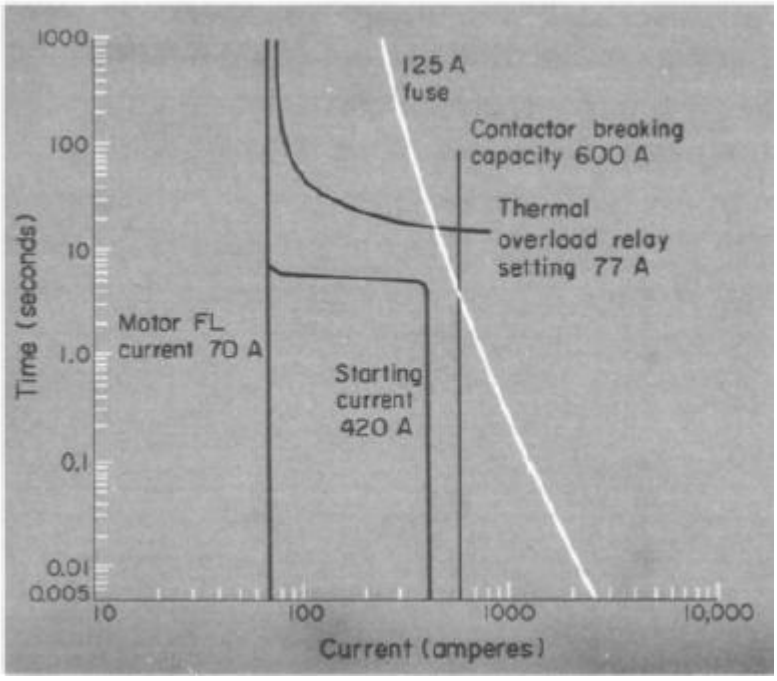



Fig. 2 Composite time/current curves

**To summarize**

1 .The fuse must be adequately rated to supply normal current to the circuit.
2. The rating must take into account any normal healthy overload conditions e.g. the starting of motors.
3. An allowance must be made if an overload occurs frequently.
4. There must be an adequate margin if discrimination between fuses is required.
5. The fuse must protect any equipment which is not rated at the full short-circuit rating of the power system, e.g. contactors, cables, switches, etc.

**Example of fuse selection**
A 415 V distribution system is shown in Fig. 3.
Lighting load - 20 kW

$$I = \frac{20 \times 1000}{\sqrt{3} \times 415} = 27.8 \text{ A}$$

Select a 32 A fuse.

Heating load - 30 kW

$$I = \frac{30 \times 1000}{\sqrt{3} \times 415} = 41.7 \text{ A}$$

Select a 50 A fuse.

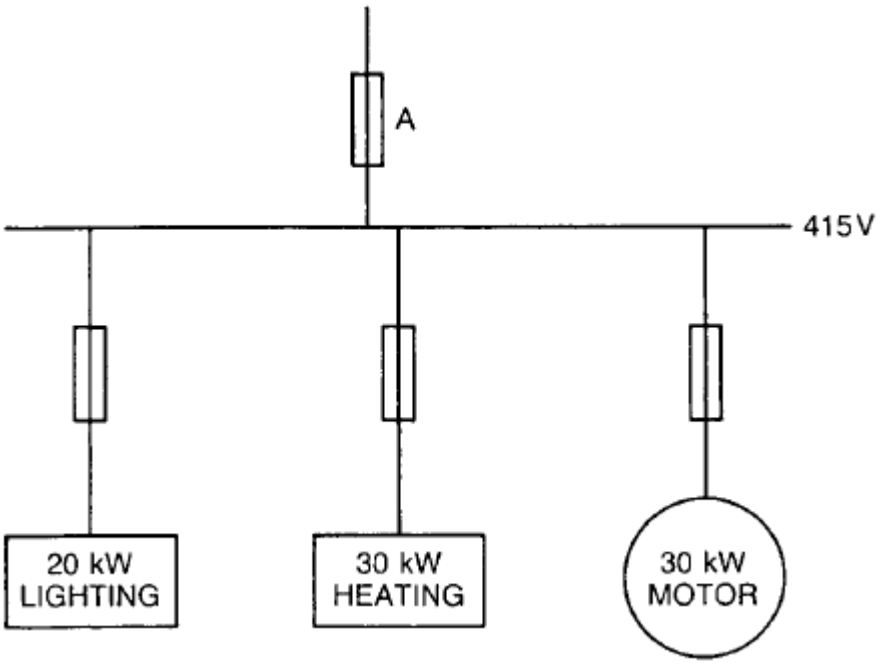



Fig. 3.

Motor 30 kW

Note that, whereas the lighting and heating loads are rated at the input power, the motor is rated at the output power. The motor input power is output power/efficiency, i.e. for 92% efficiency:

Input power = 30 / 0.92 = 32.6 kW

Also the heating and lighting loads are at unity power factor whereas the motor power factor is, say, 0.83.

Therefore the motor full load current is

$$I = \frac{32.6 \times 1000}{\sqrt{3} \times 415 \times 0.83} = 54.7 \text{ A}$$

The starting current of, say, 7 x full load current for 10 s is 7 x 54.7 = 383 A.

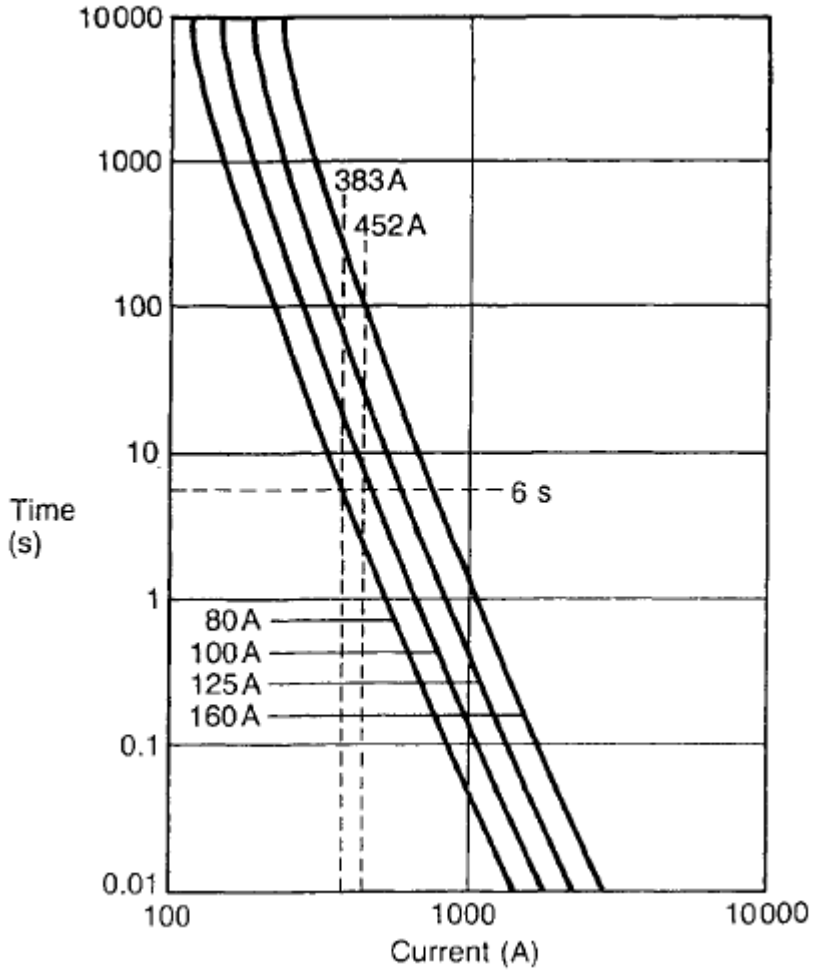



Fig. 4 Fuse time/current characteristics

From the time/current curve, Fig.4, an 80A fuse would withstand 383 A for only 6 s. Therefore a 100 A fuse, which would withstand 383 A for longer than 10s, would be necessary.
To provide discrimination the fuse at A must meet the following requirements.

1 - It must carry the normal load"

$$27.8 + 41.7 + 54.7 = 124.2 \text{ A}$$

2- It must carry the load plus the starting current of the motor:

$$27.8 + 41.7 + 383 = 452.5 \text{ A for 10 s}$$

From Fig. 4 a 125 A fuse would withstand 452.5 A for more than 10s.

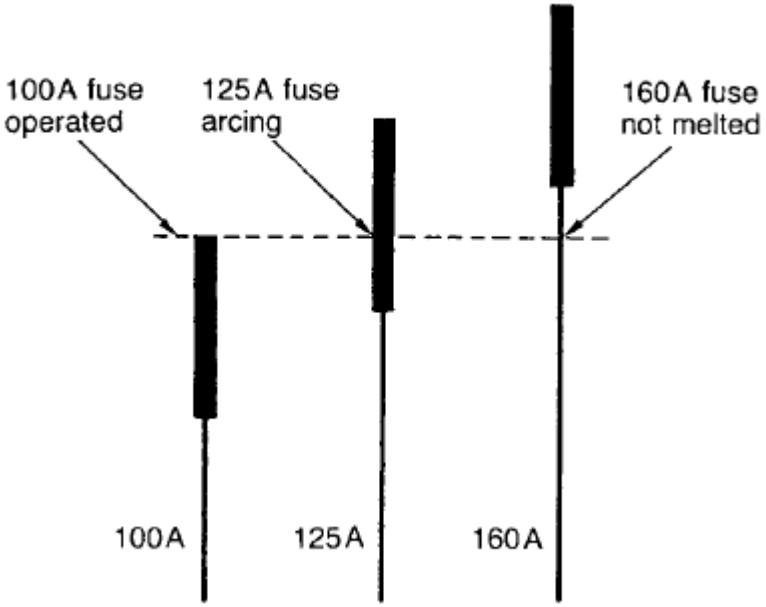



Fig. 5 Discrimination between fuses

3- The pre-arcing $I^2t$ must be greater than the total $I^2t$ of the 100 A fuse. Figure 5 shows that a 160 A fuse would be required.

# Bus Bars Protection

## Bus Protection Schemes

Bus protection is used to protect switches,disconnects,instrument transformers, circuit breakers , and other bus equipment as well as the bus itself.

There are several methods of bus protection:

- Basic Differential Protection
- Differential Protection with Overcurrent Relays
- Percentage Differential Protection
- High-Impedance Voltage Differential Protection
- Bus Partial Differential Protection

All these methods are based on KCL , namely , that the sum of all current entering a node must be zero.Consider the two situations for simple bus shown in Fig.1

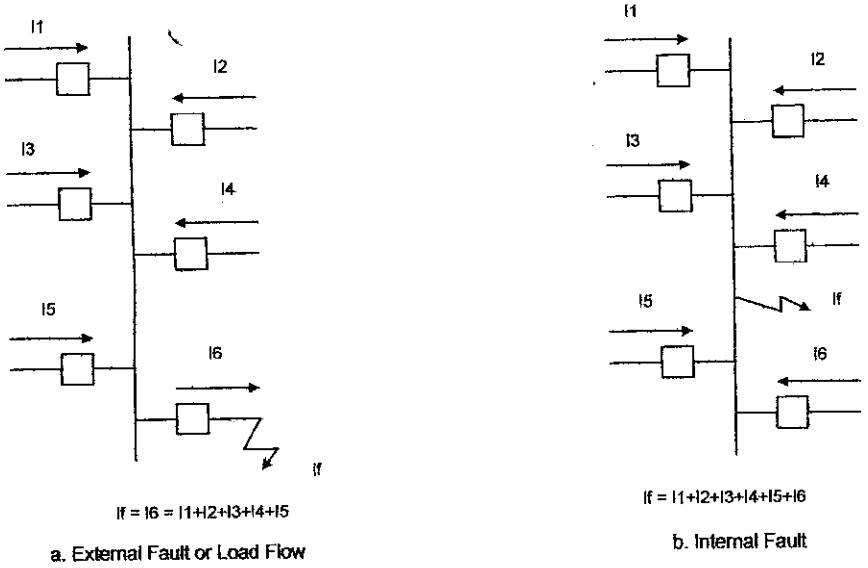



Fig.1 Simple bus arrangement

- For external fault : $I_f = I_6 = I_1+I_2+I_3+I_4+I_5$
- For internal fault : $I_f = I_1+I_2+I_3+I_4+I_5+I_6$

## Bus differential relaying Schemes:

### 1. Basic differential system

A basic differential system is shown in Fig.2. All CTs must have same ratio and polarity such that the current circulate amongst them is zero (Id=0) for all external faults. For internal fault current Id=If will flow through the relay.

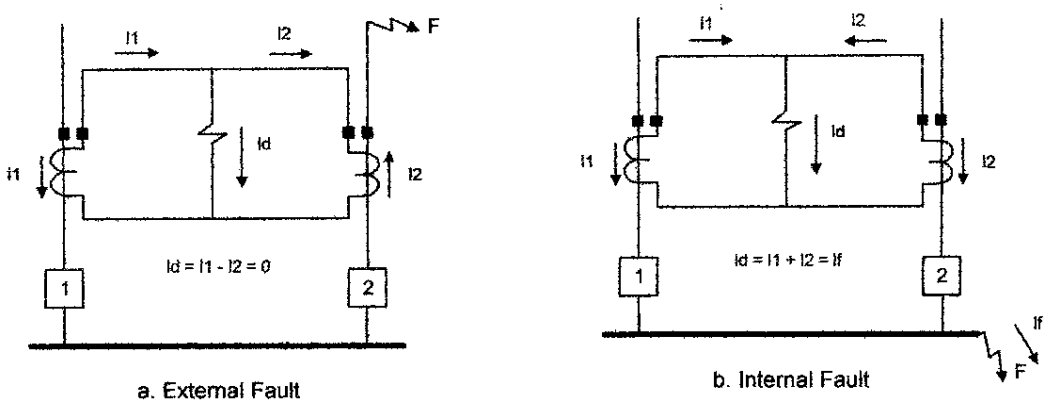



Fig.2

### 2. Bus Differential Protection with Overcurrent Relays

If the CTs behaved ideally, the differential system shown in Fig.2 would be very easy to implement using a simple overcurrent relay as shown in Fig.3.

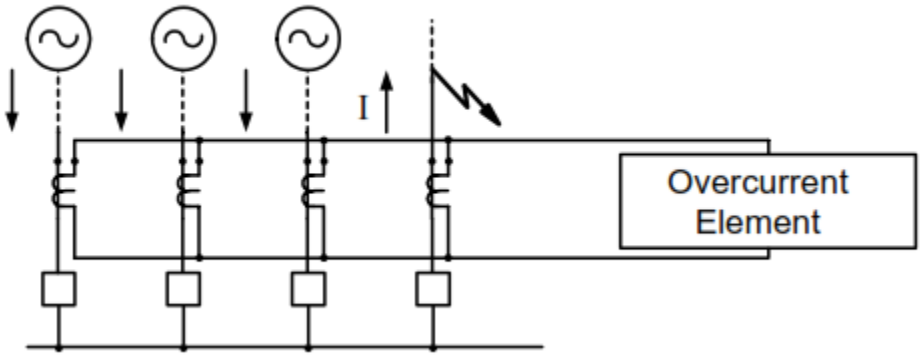



Fig.3

### 3. Bus Protection with Percentage Differential Relays

A percentage restrain differential relay takes the fact that there may be error current in differential circuit A simple percentage restrain differential relay is shown in Fig.4.

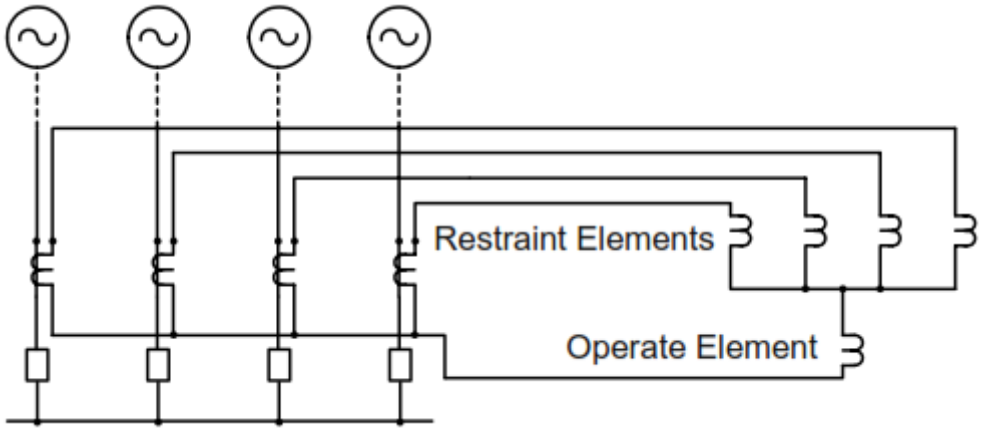



Fig.4

Consider a load bus with three outgoing feeders as shown in Fig.5 .This bus is protected by differential relay with three restrain coil .The protection scheme shown for one phase only.

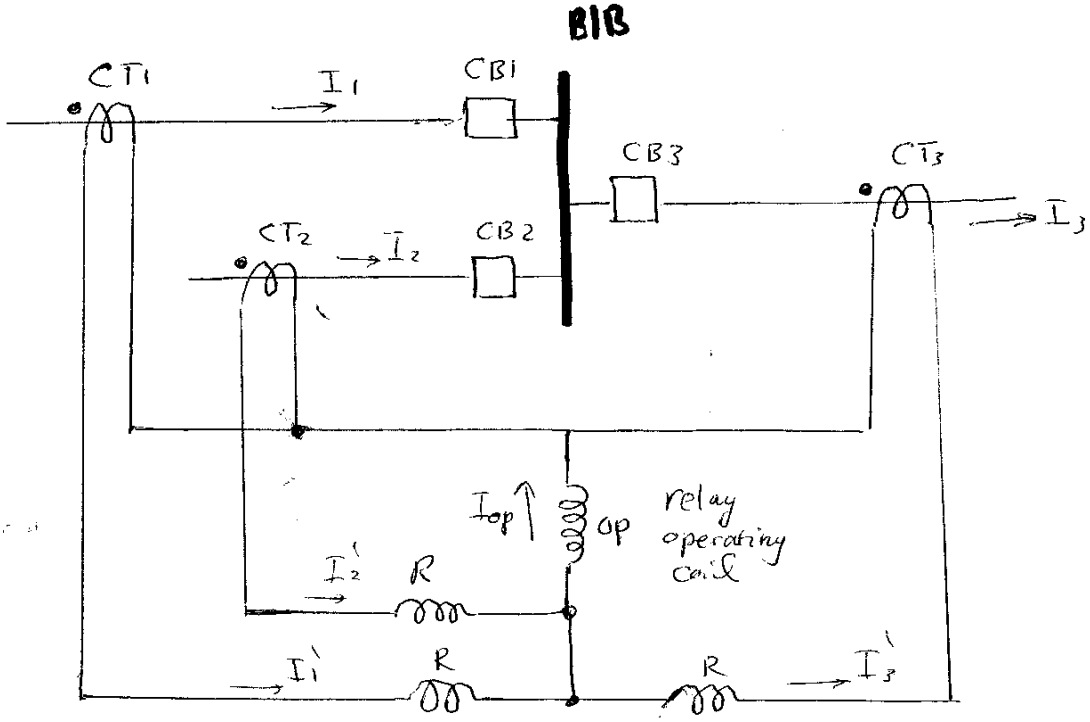



Fig.5

- When there is no fault (internal fault):

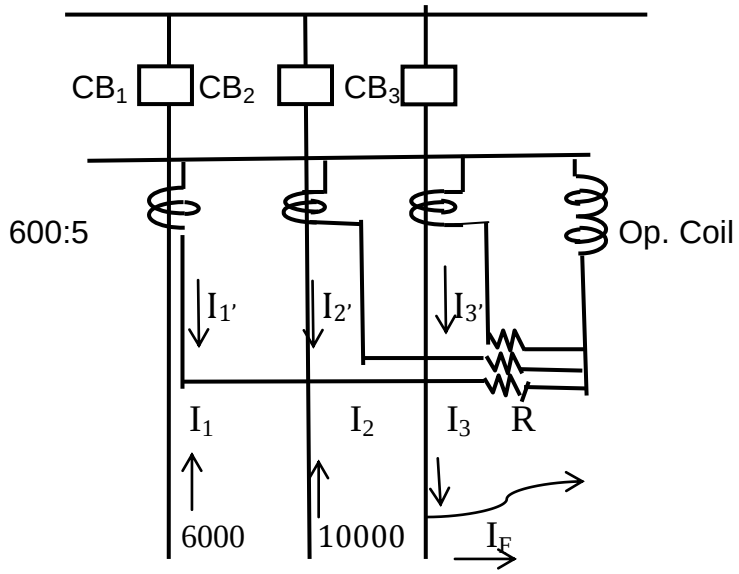
$I_1 + I_2 = I_3$

$I_1' + I_2' - I_3' = 0 = I_{op}$. The relay will not operate.

- When there is fault:

$I_1' + I_2' - I_3' \neq 0$ The relay will operate.

Example 1: for the system shown (bus protection by differential current relay) an external fault has occurred on feeder no.3, find weather, the differential relay will operate or not.




Solution:

$I_f = I_{F1} + I_{F2} = 6000 + 10000 = 16000$ A.

$I_1' = 6000 \times \frac{5}{600} = 50$ A

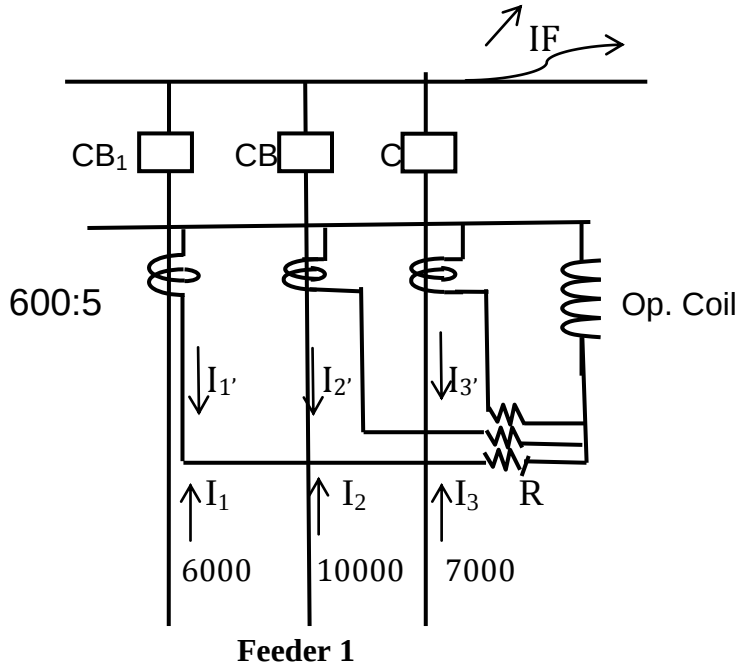
$I_2' = 10000 \times \frac{5}{600} = 83.4$ A.

$I_3' = 16000 \times \frac{5}{600} = 133.4$ A.

$I_{OP} = I_1' + I_2' + I_3' = 50 + 83.4 - 133.4 = 0$ .

Hence the relay will not operate.

Example 2: repeat example 1, if the feeder no.3 supplies 7000A current infeed to the bus and an internal fault occurs on the bus itself.




Solution:

$I_f = I_{F1} + I_{F2} + I_{F3} = 6000 + 10000 + 7000 = 23000$ A.

$I_1' = 6000 \times \frac{5}{600} = 50$ A

$I_2' = 10000 \times \frac{5}{600} = 83.4$ A

$I_3' = 7000 \times \frac{5}{600} = 58.3$ A

$I_{OP} = I_1' + I_2' + I_3' = 50 + 83.4 + 58.3 = 191.7$ A

Hence the relay will operate.

## 4. Bus High-Impedance Voltage Differential Protection

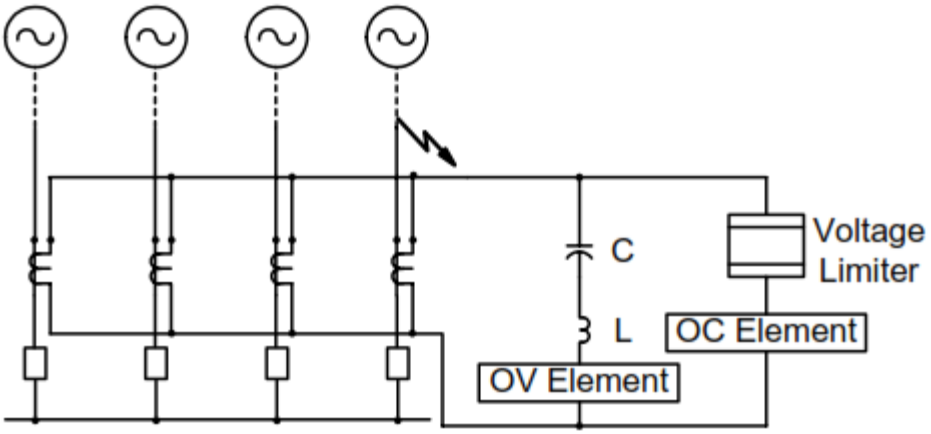



Fig.6

## 5. Bus Partial Differential Protection

- ❖ A partial differential scheme is similar to an overcurrent differential scheme, the difference being that all breakers are not monitored. This scheme is used when there are *limited sources and multiple outfeeds.*This scheme is shown in Fig.7 below.
- ❖ The scheme uses an overcurrent relay fed from paralleled CTs that only monitor the sources to the bus. The overcurrent relay is set to coordinate with the feeder relays.

- ■ Advantage: Relatively inexpensive.
- ■ Disadvantage: Slower clearing time.

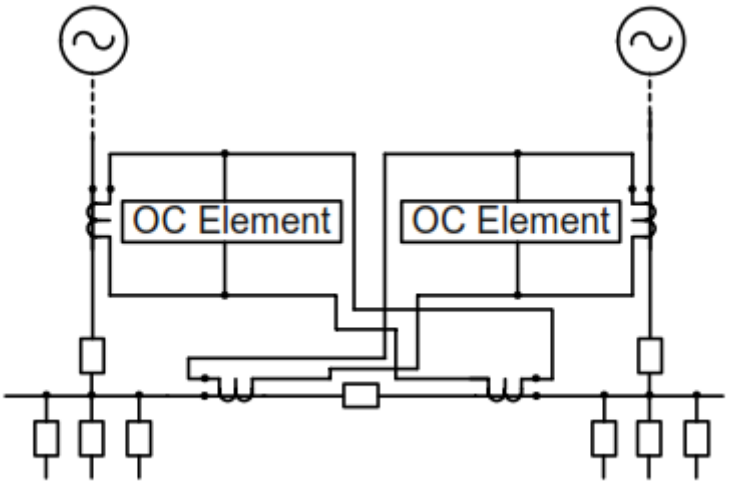



**Fig.7**